



DEVELOPMENT OF ALL-POSITION, MECHANIZED AND AUTOMATIC
FCAW SYSTEMS FOR THE FABRICATION OF OFFSHORE STRUCTURES
AND ARCTIC VESSELS

Final Report By:

D. V. Dorling
R. M. Huntley
A. B. Rothwell

Work on this project was jointly funded by NOVA, AN ALBERTA CORPORATION
and the Physical Metallurgy Research Laboratories, Canada Centre for
Mineral and Energy Technology, Energy Mines and Resources Canada.

DSS FILE NUMBER:	23SQ.23440-2-9027-5
DSS CONTRACT SERIAL NUMBER:	OSQ82-00250
CANMET SCIENTIFIC AUTHORITY:	Dr. J. E. M. Braid

JULY 1984

114pp

NOV 22 1984

MICROMEDIA



ABSTRACT

For the economical construction of offshore structures and Arctic vessels, a clear need exists for welding processes which are capable of depositing weld metal of high integrity and toughness, in a shop or site environment, and which offer significantly improved productivity, relative to the conventional shielded metal arc process. This report describes the development of mechanized and automated flux-cored arc welding systems which can be used with conventional d.c. and pulsed power sources of both transformer-rectifier and motor generator type. Three rutile-cored consumables were identified which showed excellent operating characteristics in all welding positions when operated in the d.c. mode, while none of the basic or metal-cored wires was acceptable. In the pulsed mode, these three rutile-cored wires again gave superior results, albeit at lower mean currents; only one of the basic wires had acceptable operating characteristics, and even that presented such limitations that no productivity advantage could be anticipated. For the three rutile wires, however, both d.c. and pulsed-mode procedures were developed which offered reductions of 54-62% in time to complete a 1067 mm O.D., 25 mm W.T. girth weld, relative to a conventional SMAW procedure. Test panels produced in 25 mm thick Lloyds LT60 plate, using similar procedures, gave encouraging Charpy toughness results (29-54 J at -60°C); CTOD results at -45°C were less satisfactory, however, and further optimization of consumables and/or welding procedure appears necessary in order to achieve toughness properties suitable for extremely severe service conditions, in the as-welded condition.



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1.0 INTRODUCTION

The construction of offshore structures, either fixed production platforms or mobile exploration units, follows, in many respects, standard shipyard practice, in that it involves fabrication of sub-assemblies in a shop environment and subsequent launch-site or berth erection. The stringency of the requirements for offshore oil and gas installations and the conditions in which welding has to be carried out have essentially limited the choice of welding process to mechanized submerged arc welding (SAW) and shielded metal arc welding (SMAW) for fabrication of sub-assemblies and SMAW for site erection⁽¹⁾. The application of high quality, high productivity submerged arc welding is limited to joints of simple geometry in the flat position, such as the welding of stiffened shell panels, the axial welds of large structural cans and tubulars and circumferential or girth welds when the workpiece can be rotated beneath the welding head. For out-of-position welding, both in the shop and on site, the most widely used process is still the basic, low-hydrogen shielded metal arc welding process.

The physical scale and cost of offshore oil and gas installations, together with the greater demands for positive assurance of the technical integrity of structures and vessels for Arctic service, has



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led to considerable interest in the development of welding processes and procedures which offer better productivity and improved reproducibility and control, relative to traditional, shielded metal arc welding techniques.

The attainment of adequate weld-metal notch toughness (to -60°C for Arctic service) and the prevention of hydrogen-assisted cracking are the main considerations when selecting a welding process and developing welding procedures for high-integrity fabrications. The necessity of using the SMAW process to meet these requirements in welded connections in all positions other than flat is very costly. Process deposition rate and operating factor or duty cycle are the most influential factors affecting productivity and hence welding costs⁽²⁾, and it is therefore not difficult to comprehend the potential benefits that a continuous-wire welding process and its mechanization would bring to the site, as well as shop fabrication of offshore structures and Arctic vessels.

Much can be learnt from recent developments in pipeline welding technology. For the last few years, the mechanized gas metal arc welding (GMAW) system has been used extensively on large-diameter, cross-country pipeline projects in Canada.⁽³⁾ All welds are in the fixed 5G position. Recently, a more productive means of making



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fixed-position welds between heavy-wall pipe and components for station construction was developed and successfully applied to the fabrication of compression facilities on the Eastern Leg of the Alaska Highway Gas Pipeline Project.⁽⁴⁾ Procedures for above-ground service (design temperature -45°C) were developed and applied in production, through the use of a slightly more sophisticated adaptation of the mainline orbital pipe-welding system and the gas-shielded, flux-cored arc welding process. It was the object of this present investigation to assess the applicability of the mechanized FCAW system, and its recently-developed automated variant, to the welding of offshore structures and Arctic vessels.

Flux-cored arc welding (FCAW) has a number of features of potential benefit to heavy-section structural fabrication. A number of consumables offering all-position capability have become available. Because of the mode of metal-transfer, the process is not inherently susceptible to fusion defects. Deposition rates are high and, like all continuous wire processes, it lends itself readily to mechanization; this, in turn, allows tighter control to be exercised over procedural variables.

Flux-cored wires fall into two general classes; externally-shielded types requiring the provision of a concentric flow of shielding gas,



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usually carbon dioxide or mixtures of argon, oxygen and/or carbon dioxide, and the self-shielded variety which utilize ingredients in the core of the electrode to provide a shielding gas or vapour as they decompose in the arc. The core of both types of electrode contains ingredients for fluxing, deoxidation and alloying additions.

Only the semi-automatic self-shielded FCAW process has been applied to the fabrication of offshore structures to any significant extent.⁽⁵⁾ However, productivity has been limited by the need to rely on multi-pass welding techniques to achieve adequate notch toughness properties and, in practice, the degree of control required over the execution of welding procedures to ensure consistent weld properties with this process is difficult to achieve.⁽⁶⁾

Gas shielded flux-cored electrodes of interest in the context of offshore structures and Arctic vessels generally fall into two categories; those with flux formulations based on titanium dioxide (rutile) and those based on calcium carbonate plus calcium fluoride (basic). In addition, so-called metal-cored wires have also been recently introduced. The flux formulation or slag system affects both electrode performance and the mechanical properties of the weld deposit. Rutile electrodes are generally capable of good operation



in all welding positions but, due to a relatively high concentration of impurity elements, especially oxygen, the toughness of the weld deposit has, in the past, been limited.^(7,8) The use of the lower oxygen-potential basic flux formulation would, from experience with other flux-shielded processes, be expected to improve toughness properties; however, operational characteristics and positional welding capability of basic flux-cored electrodes are the subject of some debate.^(7,9,10)

Recent developments in rutile flux-cored wires have selectively increased the percentage of basic flux components to achieve a cleaner weld deposit without degrading their operating characteristics. Further weld metal refinement is accomplished with microalloying additions of, for example, boron, with the result that the low temperature notch toughness properties of weld metal deposited by these electrodes is considerably enhanced.⁽⁸⁾ The wire used by NOVA for the mechanized FCAW of large-diameter station piping and components was an example of such a "second generation" rutile flux-cored electrode.

In order to assess the applicability of the mechanized and automated FCAW process, it was necessary to establish the handling characteristics of the available consumables in the mechanized mode



and determine whether they were capable of all-positional welding with significantly improved productivity relative to SMAW. It was also necessary to determine whether they were capable of depositing weld metal which would meet mechanical property requirements for Arctic service. This report describes investigations with both rutile and basic flux-cored wires, as well as selected metal-cored wires, using direct current and pulsed current welding techniques. The use of lower oxygen-potential shielding gas mixtures can lead to further improvements in mechanical properties, and this aspect was investigated; for these experiments, pulsed current was examined as a means to avoid the degradation in operating characteristics that can occur when an electrode is used with shielding gas mixtures other than the one for which it was designed. The ability of pulsed current to improve the operating characteristics and positional capability of basic flux-cored wires was also examined. The development and metallurgical evaluation of procedures for heavy-section structural steel, to Lloyds LT60, is described and considerations regarding quality and productivity are discussed.



2.0 EXPERIMENTAL APPROACH

The principal objective of this investigation was to determine the feasibility of mechanization and automation of the flux-cored arc welding process for the site fabrication of offshore oil and gas installations. The experimental program was divided into three parts. The first part involved the mechanization of the FCAW process; the tasks involved were:

- (i) the selection of a mechanized welding system with an all-position capability;
- (ii) interfacing the system with a range of both conventional direct current and pulsed power supplies; and
- (iii) an evaluation of the positional capabilities of a number of FCAW consumables of rutile, basic and metal cored formulation, in the mechanized mode, using both direct and pulsed current techniques.

In the second part of the program, welding procedures were developed with selected consumables in 25 mm thick large diameter pipe, in all welding positions, in the mechanized mode, and evaluated in terms of



productivity. The third part of the program consisted of adapting and interfacing a recently-developed, all-position, automated welding system to run flux-cored wires in both direct current and pulsed current modes in a site welding situation and, following the previously optimized welding procedures, using the automated system to complete test panels in 25 mm thick LT60 steel for metallurgical evaluation.



3.0 EQUIPMENT AND MATERIALS

3.1 Mechanized Welding System

The mechanized system selected for the investigation was the CRC model M-200. This system had already been successfully used in production by NOVA for the site welding of large-diameter, heavy-wall pipe and piping components. The M-200 (Figure 1) is, essentially, an orbital welding machine and travels on a 120 mm wide spring steel band. The unit has three parts; a carriage section, control-box section and welding section. The carriage section consists of a hinged base that can be adjusted for diameters from 254 mm to flat plate, a 24 V drive motor and gear box, and a cam mechanism used to latch the machine onto the band. There are also three grooved guide wheels and a knurled drive wheel that ride on the edges of the band. The control box contains three printed circuit boards that control travel speed, wire-feed speed, oscillation frequency and dwell time, and wire and gas shut-off delay. There are check buttons for each function of the unit and on and off control buttons to energize and de-energize all control circuits. A power switch applies 24 V d.c. to the circuit. A thumb-wheel control sets oscillation width and single-turn potentiometers set left and right dwell and oscillation rate. Ten-turn potentiometers control travel and wire-feed speeds.



The welding section consists of wire drive motor, oscillation motor, welding head and capacity for a 4.5 kg spool of wire. Front and end elevations and manufacturer's data are shown in Figure 2.

3.2 Automated Welding System

The automated welding system evaluated for site fabrication applications and used to complete the test panels in part three of the investigation was the CRC model M-1000. The M-1000 (Figure 3) is a recent development based, as was the M-200, on the CRC pipe welding system and, again, consists of adjustable carriage, control and welding sections. Front and end elevations and manufacturer's data are shown in Figure 4. The control section, however, is an adaptive, closed-loop feedback system; an RCA 1802, 8-bit microprocessor provides all major welding control. The travel speed, wire-feed speed, electrical stick-out, torch oscillation rate and sidewall dwell are programmed into the computer by means of a keypad. Both wire-feed and travel carriage are driven by pancake motors to an accuracy of 0.5% of set speed through closed-loop control using an optical encoder. Torch oscillation is linear with the torch driven by stepper motors through precise gear transmission; the computer counts the number of steps each motor takes from its home position and in this manner the torch location is accurately



defined in a three dimensional matrix. Before starting a welding pass, the M-1000 does a profile measurement of the groove to be filled (Figure 5). The operator positions the torch over the groove and the M-1000 then finds the bottom and sides of the groove using electrical sensing with an internally generated 10 V current source. On commencement of welding, the M-1000 measures the peak current at the centre of the oscillation sweep and uses that value to control the arc length. It does this by adjusting the torch-to-work distance such that the peak current measured on consecutive sweeps remains constant. It also uses this peak current measurement as a reference value for tracking the sidewall of the groove. As the arc approaches the sidewall, the arc length decreases causing an increase in the peak current with respect to the reference value. The M-1000 senses this and reverses the direction of the oscillation sweep.

3.3 Welding Power Sources

The mechanized and automated welding systems were interfaced with both transformer-rectifier and engine-driven welding power sources. A three-phase grid system in a shipyard will enable the rectifier-type power sources to be used on site; however, in situations where three-phase power is not readily available, engine-driven welding generators are required. The d.c. rectifier



used in the investigation was the Lincoln Idealarc DC-600, an SCR-controlled power source capable of both constant potential and constant current output of 600 A at 44 V and 100% duty cycle. The engine-driven welding generator was a Miller Trailblazer 550, combination constant current-constant potential d.c. welding generator driven by a four cylinder, liquid-cooled, Continental diesel engine. Rated constant current output is 350 A at 40 V and rated constant potential output is 400 A at 36 V, 100% duty cycle.

For pulsed welding, two power-supply units were investigated. The first was the OTC Transistarc MM350 (Figure 6a), a commercially-available rectifier unit which features switching transistor control of current output. The pulse structure is factory programmed and the wire-feed speed is linked to pulse frequency to achieve a "one-knob", synergic-type control. Rated output is 350 A at 36 V, 50% duty cycle. The second unit was an add-on, transistorized power-regulator (Figure 6b), custom built for NOVA, by Espel Inc., to a design based on the Welding Institute of Canada frequency-modulated pulsed gas metal arc welding system. It is, essentially, a bank of thirty-two power transistors controlled by an electronic circuit. It has three front panel controls that set the peak current between 100 and 500 A, time at peak between 1 and 8 ms and background current between 15 and 45 A and a fourth control for voltage/arc length trim. As originally



designed, the regulator automatically adjusted the frequency, and thus the mean current, for the diameter of wire and wire-feed speed selected.

3.4 Parent Material

Consumable evaluation and procedure development was carried out on one length of 1067 mm O.D. x 25 mm W.T., CSA Z245.1 Grade 414 MPa pipe. Test panels for metallurgical evaluation were prepared from 25 mm thick Lloyds LT60 steel plate, supplied by Algoma Steel, the composition of which is given in Table 1.

3.5 Welding Consumables

The AWS specifications for electrodes for the flux-cored arc welding of carbon steels, A5.20-79, and low-alloy steels, A5.29-80, classify wire types according to shielding, welding characteristics, mechanical properties and chemical composition. Selection of flux-cored consumables for the investigation was limited to the gas shielded T1 (all-position, rutile) and T5 (limited position, basic) types. Two metal-cored wires, one of which is not covered by the AWS specifications, were also included. Details of the consumables selected are given in Table 2. The AWS classification requirements for the wire types selected are given in Tables 3 and 4.



3.6 Instrumentation

Welding current and voltage were continuously monitored using either a CRC Arc Data Analyzer or a "Briefcase Monitor" custom built for NOVA by the Welding Institute, UK, both of which included arc-time meters. Welding voltage was measured between the contact tip and workpiece in all cases. For pulsed welding evaluations, pulse parameters were continuously monitored using a Gould OS 4000 digital storage oscilloscope. Additional custom metering was used for the monitoring of pulse frequency.



4.0 INTERFACING AND COMMISSIONING OF WELDING SYSTEMS

4.1 Mechanized Welding System

Interfacing for the M-200 and the conventional d.c. power sources was supplied by CRC and consisted of a step-down transformer to supply the 24 V power necessary to operate the travel, wire feed and oscillation motors and gas solenoid. The transformer assembly, which also included the gas solenoid, was mounted on or near the power source and the 24 V power, welding power and shielding gas supplied through an umbilical. The transformer assembly also contained a 24 V remote contactor relay and a printed circuit board which controlled the sequencing of the various functions of the M-200; for example, when the weld start button was pushed, the gas solenoid was first activated, the welding contactor closed and wire feed, oscillator and, finally, travel motor powered. On completion of welding, the sequence was reversed. When using the M-200 with the engine-driven power source, an electronic voltage regulator was added to set and accurately maintain the required arc voltage.

The same interfacing, with the exception of the voltage regulator, was used to connect the OTC Transistarc pulsed welding power source to the M-200. However, the Transistarc is, essentially, a "synergic"



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system with integral wire feeder and is designed for semi-automatic gas metal arc welding. It is a frequency-modulated system and the synergy between the one-knob frequency control and the OTC wire-feeder ensures that the burn-off rate of the electrode is matched by the wire feed to produce stable arcing conditions as frequency of pulses is varied. On connecting the M-200 to the Transistarc power source, the synergy was lost, as the M-200 has independent control of wire-feed, and the OTC wire-feeder had to be disconnected. A series of tests had to be conducted to determine those wire-feed settings on the M-200 that would exactly match the burn-off rate of the selected cored wires for various pulse frequencies prior to conducting the consumable evaluation program.

In the case of the transistor regulator, it was first necessary to connect this to a host power source. With a rectifier unit, this simply involved connecting positive and negative output terminals of the host power source to the appropriate quick-connect sockets on the front panel of the regulator. Additional control connections had to be made to effect remote turn-on and voltage control of the power source output by the transistor regulator. The only additional connection to the M-200 was for on/off control of the regulator through the wire-feed start relay.



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The regulator has circuits to protect the transistors from overheating and excess voltage and current. One of the protective circuits is a signal which attempts to control the voltage of the d.c. power-source. This circuit did not work with the Miller Trailblazer engine-driven power-source, even though the Trailblazer was modified with the electronic voltage-regulator supplied by CRC. The problem was due to interacting time constants and the wide variation of power factor in the load presented to the Trailblazer by the regulator input-capacitors. The result was that the voltage-regulator caused the output of the Trailblazer to oscillate, an unstable and potentially dangerous situation. To avoid the problem, the Trailblazer was operated in the standard, minimum-slope mode of regulation. Care had to be taken not to set the voltage too high, otherwise the regulator would shut down due to overheating.

Operational problems with the transistor regulator were revealed early in the consumable evaluation stage. The main problem was the difficulty in setting and maintaining welding and pulse parameters that would give stable arcing conditions, even deposition and freedom from spatter. This was found to be caused by erratic and very large changes in pulse frequency. Since pulse frequency is approximately proportional to mean current, this resulted in fluctuations in mean current as high as 100%. These fluctuations were a result of the



pulse frequency modulation method used in the transistor regulator. The arc voltage is measured during the background current period and then compared with a voltage reference signal set by a front panel potentiometer. The difference is amplified and filtered and then used to adjust the pulse frequency. However, due to large variations in background arc voltage, even at essentially constant arc lengths, this method resulted in large fluctuations in pulse frequency and, hence, in mean current. To overcome the problem, the arc voltage feedback was disconnected and the frequency modulation disabled. The regulator was then modified to enable the frequency to be set manually, by front panel control, to a value calculated to provide the required mean current for the wire-feed speed selected.

4.2 Automated Welding System

The CRC M-1000 was interfaced only with the Trailblazer 55D or with the transistor regulator with the Trailblazer as host power source. Interfacing for the M-1000 is built into the system and there are a number of voltage control options to enable the machine to be mated with various solid-state, rectifier-type power supplies. However, for the Trailblazer, none of these were suitable and the electronic voltage-controller designed for the M-200 had to be utilized. This meant that the M-1000 forfeited control of voltage, which could only



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be set at the power source through the voltage regulator. For pulsed welding application, Figure 7 shows the interconnection of the three units; the M-1000, the transistor regulator and the Trailblazer 55D. The heavy lines indicate the main current path. Also shown are the main pulse control blocks.

When the first attempt was made to use the transistor regulator with the M-1000, there was a problem with groove sidewall tracking; the automated welder was unable to sense any current change as the arc approached the sidewall, causing the arc to climb the sidewall and become unstable. The lack of current change, as the arc shortened at the sidewall, was due to the regulator operating as a current source and tightly regulating the current. The M-1000 requires a voltage source during peak current time so that it can sense changes in current due to arc length changes. This problem was solved by operating the transistors in the saturated switch mode during peak current time; the transistors were fully on and no longer controlling the current. The peak current was then controlled by the output voltage of the Trailblazer.



5.0 EXPERIMENTAL PROCEDURE

5.1 Electrode Evaluation

The positional capability and welding characteristics of the various cored wires were evaluated using the M-200 by depositing beads at the first or second fill pass level in a standard 60° bevel in 1067 mm O.D., 25 mm W.T. pipe in the 5G orientation. All welds were deposited in the 45° overhead position, this being the most difficult when welding with a vertical-up progression. The pipe was rotated, when necessary, between weld deposits. Welding parameters were systematically adjusted to cover the entire range of potential welding conditions as illustrated in Table 5.

The electrodes were first evaluated using conventional d.c. power as supplied by the Idealarc DC 600, with the performance of selected consumables being verified with the M-200 connected to the Trailblazer 55D. Shielding gas was 75% argon, 25% carbon dioxide throughout and welding polarity was chosen according to the consumable manufacturer's recommendations. Acceptable welding conditions were determined through consideration of arc stability and bead profile, and the operating range of each consumable, in terms of welding voltage and current/wire-feed speed, was defined.



Those consumables for which acceptable welding conditions could not be achieved with the conventional d.c. power source were then evaluated using pulsed current and the UTC Transistarc. The evaluation procedure was as before with the exception that 92% argon, 8% carbon dioxide was used as the shielding gas. Further optimization of the positional capabilities of these consumables was attempted using the transistor regulator with the Idealarc DC 600 as host power source. This combination gave increased flexibility for pulsed welding applications when compared to the Transistarc, in that the influence of pulse height, width and background current could be investigated.

5.2 Procedure Development and Evaluation of Production Aspects

Based on the results of the consumable evaluation, three electrodes of rutile formulation were selected for further investigation in both d.c. and pulsed current modes of operation together with one electrode of basic formulation for which an all-position welding capability could be achieved in the pulsed current mode. Procedures were developed for completing girth welds in 1067 mm O.D., 25 mm W.T., Grade 414 MPa pipe, as a prerequisite for the welding of the 25 mm thick test panels and in order to generate productivity data which, in combination with production data from field experience with both mechanized FCAW and SMAW in this diameter and size of pipe,



would provide a basis for economic comparison. The machined weld preparation was a 60° included angle with a 3.2 mm land and 3.2 mm gap. Root and hot passes were deposited using E55010-G SMAW electrodes. Mechanized FCAW procedures for filling and capping were chosen to maximize productivity with wire-feed speeds at the high end of the previously defined parameter envelope. Travel speeds were based on maintaining the arc at the leading edge of the weld pool and oscillation rate and dwell times were selected for optimum sidewall fusion and overall bead appearance.

Weld metal deposition rates were determined from bead-on-plate trials on 6.4 mm thick mild steel in the flat position.

5.3 Metallurgical Evaluation

5.3.1 Welding Procedure

Six test panels, 1 m long by 1 m wide, were prepared in 25 mm thick Lloyds LT60 plate. The edge preparation, illustrated in Figure 8, was produced by machining and the test panels were assembled as shown in Figure 9, with 50 mm by 25 mm strongbacks to prevent rotation about the weld. The test panels were welded in the vertical position using the CRC M-1000 automated welding system. The welding



procedures adopted for the three consumables selected for metallurgical evaluation were essentially the same as those developed for the 1067 mm O.D., 25 mm W.T. pipe, with the exception that a backwelding technique was adopted for the root in place of the SMAW root and hot pass; the 60° included angle bevel was filled and capped, the test panel turned, the strongbacks removed, the root arc-air gouged to sound metal, dye penetrant checked and the backweld completed with the M-1000. No preheat was applied and the interpass temperature was 200°C maximum as measured 25 mm from the weld preparation. Three test panels were completed using conventional d.c. power, with the M-1000 connected to the Trailblazer 55D, and three using pulsed current with the M-1000 connected to the transistor regulator and the Trailblazer as host power source.

5.3.2 Mechanical Testing

Each welded test panel was sectioned for mechanical testing as shown in Figure 10. Two all-weld-metal tensile testpieces of 12 mm diameter to ASTM A370 were extracted from 2 mm below the plate surface, as shown in Figure 10, and tested at 20°C. Yield strength, ultimate tensile strength, percentage elongation and percentage reduction of area were measured. Fifteen Charpy V-notch specimens were prepared according to ASTM E23 with the notch positioned at the



centre of the weld and the notch plane parallel to the weld direction and perpendicular to the plate surface. The Cv specimens were extracted 2 mm below the plate surface as illustrated in Figure 10 and were broken at various temperatures to obtain transition curves for each wire evaluated. Three B x 2B CTOD specimens were prepared with the notch at the weld centreline and in the through-thickness direction and were tested in accordance with BS 5762 at a test temperature of -45°C. Macrosections were prepared for examination of bead profiles, potential for defects and weld run sequence, and a hardness survey was conducted at a load of 0.5 kgf.

5.3.3 Chemical Analysis

Broken tensile specimens were used to supply weld metal for chemical analysis. Non-gaseous elements were analyzed spectrographically and gaseous elements by the high temperature, inert-gas fusion technique.

5.3.4 Metallographic Examination

Transverse sections were prepared by mounting in bakelite, wet grinding on graded silicon carbide papers and polishing on rotating cloth pads, using 6 micron and 1 micron diamond dust pastes. The sections were then etched in 2% nital for identification of the microstructural features present.



5.3.5 Weld Metal Hydrogen Content

The diffusible hydrogen content of weld metal deposited by the three consumables was determined using the IIW mercury method. Test welds were deposited using d.c. power at 22 V, a wire-feed speed of 7620 mm/min., and travel speed of 200 mm/min.



6.0 RESULTS

6.1 Electrode Evaluation

The results of the electrode evaluation using a conventional d.c. power supply are summarized in Table 6. Acceptable welding conditions in the 45° overhead position could be obtained over a range of wire-feed speed and voltage for those consumables of rutile formulation. They all gave stable arcing characteristics, low spatter and flat to slightly convex bead configurations within this range; at lower wire-feed speeds, some arc instabilities occurred, while at the higher wire-feed speeds, the bead became increasingly convex. The electrodes produced a full slag cover, which was light, friable and, consequently, easily removed. The handling characteristics of the electrodes did not vary noticeably when operated with either the rectifier or engine-driven power source. The Alloy Rods, Kobe and Oerlikon rutile consumables were superior to the others in terms of handling characteristics and potential for defects and were selected for further investigation.

With both the basic flux-cored and metal-cored consumables, no combination of voltage, wire-feed speed, travel speed and oscillation rate and dwell times was capable of producing acceptable bead



profiles. Performance, in general, did not differ greatly from one electrode to another in the 45° overhead position, and the positional capabilities of these wires were severely limited by the fluidity of the molten weld puddle. Changes in wire-feed speed had the greatest influence on arc and weld characteristics. At low wire-feed speeds, the arc was unstable and little metal was transferred to the weld pool; molten droplets fell off the end or ran back down the wire. Increasing the wire-feed speed stabilized the arc and metal transfer but, at that point, the weld puddle could not be supported and would "grape" (Figure 11a) or drop completely out of the groove.

The results of evaluating the three selected rutile flux-cored wires and the three basic and two metal-cored wires with pulsed current using the UTC Transistarc power source are summarized in Table 7. The welding characteristics of the rutile electrodes were excellent with stable arcing and little or no spatter. However, the weld puddle was noticeably more fluid and the arc less penetrating under pulsed welding conditions, with the result that the maximum wire-feed speed/mean current that could be used without producing an excessively convex bead was significantly reduced when compared to d.c. welding. Of the basic and metal-cored consumables, an acceptable bead profile (Figure 11b) could be obtained only with the Alloy Rods T85-C1 electrode at low wire-feed speeds and low travel



speeds. The operating range was narrow with small changes in wire-feed/pulse frequency resulting in either arc or weld pool instability, to the detriment of bead appearance.

An attempt was made to expand the operating envelope of the three rutile wires and the T85-C1 basic electrode by optimizing pulse structure through the use of the transistor regulator coupled to the DC 600. At this stage of the investigation, the transistor regulator was still operating in the frequency modulated mode of pulsed current control, and it was not possible to set and maintain a stable arcing condition in the 45° overhead position due to the large, erratic changes in frequency that occurred. With the frequency modulation disabled and pulse frequency set by front panel control, the welding characteristics of the rutile consumables were, again, excellent and the precise pulse structure had only a minor effect on the parametric envelope. Background current, however, was found to have considerable influence on arc "stiffness" and penetration and the background current was subsequently set on the maximum for the unit of 45 A for all three wires. The remaining pulse parameters were optimized as shown in Table 8. In summary, a pulse of 410 A at 4 ms duration repeated at around 90 Hz gave the best welding characteristics for the 1.2 mm diameter wires, whereas 320 A at 5 ms was determined most suitable for the 1.4 mm wire in terms of arc



stability, smoothness of metal transfer, freedom from spatter and weld puddle control. Changes in pulse structure failed to improve the operational characteristics or expand the parameter envelope of the basic T85-C1 wire, primarily due to the fluidity of the slag and the "softness" of the arc; at the slow travel speeds necessary to produce a uniform bead profile, the slag would flow in front of the arc at a sidewall, the arc would bridge the slag between the weld pool and sidewall, and result in slag entrapment.

6.2 Procedure Development and Evaluation of Production Aspects

The procedures developed for completing girth welds in 1067 mm O.D., 25 mm W.T. pipe are included in Tables 9 to 15. The welding parameters were chosen to maximize productivity while remaining suitable for completing the whole circumference in the 5G position without significant change. Full joint completion times were then calculated based on a 70% operating factor, a conservative figure arrived at through production experience, and are compared with a true joint completion time for a shielded metal arc weld, as measured in production, in Figure 12. The procedure for completing the shielded metal arc weld is given in Table 16. A girth weld with the basic T85-C1 wire proved difficult to complete, requiring frequent changes of gas nozzle and contact tip due to heavy spatter, and considerable grinding between passes due to entrapment of slag. The



difficulties were not limited to the 45° overhead position; the fluidity of the slag, and the apparent affinity of the arc for the sidewall in the presence of slag, gave problems in all welding positions. A comparison of measured arc time and downtime for cleaning and grinding resulted in a calculated 37% operating factor, which was used to estimate the total joint completion time given in Figure 12. As can be seen from the figure, the basic flux-cored wire offers little advantage over SMAW and subsequent sectioning revealed considerable slag entrapment and lack of fusion. Further use of this consumable with mechanized or automated FCAW was not pursued.

Weld metal deposition rates from the bead-on-plate trials are given in Table 17. In all cases, the deposition rates when using the rutile wires with d.c. were greater than those for pulsed application, reflecting the difference in wire-feed speed adopted, based on bead appearance in the critical 45° overhead position.

6.3 Metallurgical Evaluation

6.3.1 Welding Procedure

The welding procedures used to complete the test panels in the 25 mm thick Lloyds LT60 with the Alloy Rods, Kobe and Oerlikon rutile



flux-cored wires, with both d.c. and pulsed power, are given in Tables 18 to 23. The procedures followed, as closely as possible, those developed for the 1067 mm girth welds in terms of fill pass welding parameters and bead placement. All passes were deposited with the CRC M-1000 automated welding system.

6.3.2 Chemical Composition

The results of the all-weld-metal chemical analyses are shown in Table 24. All three consumables are microalloyed to varying degrees with titanium and boron, with the Kobe DW 55L deposits showing the highest level of residual titanium at 0.079% and the Alloy Rods II 80Ni-1 the lowest at 0.031 - 0.035%. At 0.0017%, the boron content of the Kobe deposits was approximately half that of the deposits from the other two wires. Both the Alloy Rods and Kobe wires are alloyed with nickel, whereas the Oerlikon SF-1 deposit showed slightly higher manganese and silicon contents, but only residual nickel. The Kobe deposits were significantly lower in carbon, and the high copper content of the Oerlikon deposits reflects the fact that the SF-1 is copper-coated. Weld metal oxygen contents were relatively high at 0.041 - 0.088%; however, this is to be expected with rutile flux systems. The only significant variation attributable to pulsed current operation is a slight reduction in



oxygen content, which results from the lower oxygen potential gas mixture used for pulsed welding (92A-8CO₂ as opposed to 75A-25CO₂).

6.3.3 Mechanical Testing

Tensile test results are presented in Table 25. All deposits showed yield strengths in the range 620-710 MPa; the values are somewhat higher than would be considered ideal for the 355 MPa LT60 plate, but reflect the alloy systems incorporated in the wires and the philosophy of enhancing low-temperature toughness properties through grain refinement. The Oerlikon SF-1 deposits were marginally lower in ductility, otherwise there was little difference between the consumables or between deposits made with direct or pulsed current.

The detailed Cv impact results are presented in Tables 26 to 28 and the Cv energy transition curves illustrated in Figure 13. Only the Kobe DW 55L deposits consistently exceeded 40 J at -60°C, although all deposits met 27 J at that temperature. The Oerlikon SF-1 deposits gave the lowest upper shelf energy, consistent with the results of the tensile tests and measured weld metal oxygen content. Again, there was no consistent trend in properties that could be attributed to pulsed operation.



The first set of CTOD tests completed did not meet the requirements of BS 5762:1979 because of irregular crack fronts caused, it was suspected, by residual stresses which varied through the specimen thickness. The problem was resolved on a second set of specimens, machined from a repeat of the first test panel, by compressing the ligament below the notch, prior to fatigue cracking, by an amount equal to 1% of the specimen thickness. A 13 mm diameter platen was used to produce an indent depth equivalent to 0.5% of the specimen thickness on each side, and thereby provide a sufficient amount of mechanical stress relief to ensure uniform fatigue crack growth. Previous work⁽¹¹⁾ has indicated that this type of local precompression is effective in minimizing the effects of residual stresses during fatigue cracking, but has no consistent effect on the measured values of fracture toughness. The results of the CTOD tests at -45°C for all of the welded test panels are shown in Table 29. -45°C was chosen as the CTOD test temperature because of its wide acceptance as a design temperature for above ground or "in-air" welded fabrications. In addition, at temperatures significantly below this level, it is likely that most, if not all, of the deposits under investigation would give lower shelf behaviour, thus impairing the ability of the CTOD test to discriminate between them. As can be seen from the table, the best performance was obtained with the Kobe DW 55L wire operated in both d.c. and pulsed modes.



The detailed hardness results are presented in Tables 30 to 35 and summarized in Table 36. Maximum hardness values for the weld deposits were in the range 240 - 344 Hv 0.5. The subsurface regions of the Alloy Rods Dual Shield II80Ni-1 exhibited the lowest measured hardness and, with the exception of the Kobe pulsed deposit, the root regions were marginally higher in hardness than the subsurface. These results are not inconsistent with the procedures used to complete the test panels when heat input is considered on a per run basis (Tables 18 to 23).

6.3.4 Metallography

Figures 14 to 16 show macrographs of the six test welds completed. Fusion characteristics were good and the welds free from defects. When completing the fourth test panel, problems were experienced with the cap and fixed width routines of the CRC M-1000 automated welding system. The cap-pass routine is designed to provide increased sensitivity to loss of sidewall during the capping pass; also, for split cap-passes, single sidewall tracking can be selected with a fixed width weld using the cap-pass routine. For capping in situations where there is insufficient sidewall remaining to enable the M-1000 to track, a fixed width routine can be selected which provides a constant weld width with no centreline or width



corrections. A problem with the lateral position encoding software caused irregularities in the bead width on split cap and/or fixed width cap routines, with the results illustrated in Figure 15.

Figures 17 to 19 show representative microstructures taken from the upper fill passes to coincide with the location of the Cv notch. There were no discernible differences between d.c. and pulsed weld deposits; only the d.c. deposit microstructures are presented. As is to be expected with a multi-layer deposit, the microstructure consisted of as-deposited regions and regions refined by subsequent weld runs. The Alloy Rods deposits consisted of grain-boundary ferrite and ferrite side-plates together with acicular ferrite of varying degrees of coarseness in the primary grain interior. The reheated regions were a mixture of relatively coarse acicular and equiaxed ferrite. The Kobe wire produced a predominantly lath microstructure although of a more interlocking nature, as opposed to large colonies of ferrite with the same orientation. Reheating by subsequent weld runs resulted in large areas of fine, equiaxed ferrite. The as-deposited regions of the welds completed using the Oerlikon wire consisted entirely of a relatively fine acicular ferrite and the reheated regions a mixture of fine acicular and equiaxed ferrite.



6.3.5 Weld Metal Hydrogen

The results of weld metal hydrogen determination over mercury are given in Table 37. All three wires gave deposited metal diffusible hydrogen contents of less than 10 mL/100 g, with the Oerlikon wire, which is of seamless construction, producing the lowest hydrogen content of 2 mL/100 g.



7.0 DISCUSSION

The requirement for a high-speed, high deposition-rate joining process for the girth welding of large-diameter cross-country pipelines led to the development by CRC Automatic Welding of their mechanized GMAW pipeline welding system. This consists of an internal welding machine integrated with the internal line-up clamp and a series of orbital welding machines or "bugs" for the external passes. The "bugs" had to be lightweight, portable, yet rugged, in order to meet the demands of the spread method of pipeline construction. The modification of the pipeline welding system to meet the needs of other industrial welding applications resulted in the CRC M-200, an equally rugged, more versatile tool capable of consistent operation in all positions in the site welding situation. The fact that the system can be operated remote from the power supply makes it eminently suitable for launch-site or berth fabrication. 30 m service leads were used throughout this investigation and greater separation distances can be tolerated as long as the appropriate size and rating of both welding and 24 V service cables are selected.

As well as imposing less physical strain on the welder and offering considerable improvements in productivity, mechanized welding systems



lend themselves to much improved standardization of welding variables, relative to SMAW techniques. With increasing reliance on fitness-for-purpose concepts in high integrity fabrication, the consistent attainment of specific weldment properties in production (and hence, strict adherence to specified procedures) takes on much greater importance.

The mechanized system still requires the supervision and intervention of the operator to adjust for variations in welding parameters, tracking or joint dimensions. Further improvements in productivity and quality are possible if the welding operation can be totally automated, i.e., the system can be programmed to complete the welding task without human intervention. Other reasons for seeking fully-automated solutions to welding problems are the need to work in confined spaces and the often unpleasant environment of many arc welding tasks.

The CRC M-1000 automated welding system was developed from the M-200 and possesses all of the attributes of the mechanized system, in terms of all-positional operation, portability and ruggedness, that make it a candidate for the fabrication yard. The three-dimensional seam-tracking capability of the M-1000 opens up the possibility of a more controlled and productive means of welding not only connections



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of simple joint geometry, but also more complex sub-assemblies such as brace to column connections on offshore structures. The M-1000 is a very recent development and has yet to be used in production. However, it is being evaluated at two U.S. shipyards and both are putting considerable development effort into tailoring the system to their own specific requirements.

The system performed well during the production of the LT60 test panels for metallurgical evaluation, with the exception of the one problem with lateral drift of the welding head when running fixed-width and cap routines; this, as mentioned earlier, was solved through software modification. Capping with fixed-width routines can still present a problem if the weld preparation, or its position relative to the track, varies. The system purchased by NOVA was supplied with custom programming to override the automatic seam-tracking routines and enable the unit to be operated in a mechanized mode and "steered" via input through the keypad. However, this is not a satisfactory solution for production applications as the computer is, ideally, located remote from the welding operation. In the meantime, CRC have developed a steering system that will mount on to the welding carriage; it overrides the seam-tracking and incorporates left and right movement at the touch of a button, as well as voltage (arc-length) control. This will replace NOVA's "mechanized" program.



The fixed-position welding procedures developed in the investigation and used for test panel production were optimized for the 45° overhead, and subsequently remained unchanged irrespective of welding position. For the welding of large-diameter tubulars, further improvements in productivity may be gained if the procedure is modified around the circumference. With the present system, the procedure can be changed while the arc is running, but only through the keypad. A future program for the M-1000 will look at the development of a multi-schedule procedure capability, together with position encoding hardware and software. However, these types of improvements will require a more powerful microprocessor system, with attendant increased development and hardware costs.

The mechanized and automated welding systems are capable of running both solid and flux-cored wires. However, in positional welding using short-circuiting techniques, the solid wire GMAW process is susceptible to lack-of-fusion defects. In addition, the high oxygen-potential gas mixtures required to enhance fusion characteristics limit the toughness of the deposited weld metal.⁽¹²⁾ Pulsed GMAW offers the potential for reduced incidence of lack of sidewall fusion, through improved metal transfer characteristics, and better toughness properties, through the use of lower oxygen-potential gas mixtures, and this is to be the subject of a further cost-shared



research program. The FCAW process does not have a tendency to lack-of-fusion nor does it suffer from other operational problems inherent in the solid-wire GMAW process, such as excessive spatter and susceptibility to porosity due to reduced gas shielding efficiency. Gas shielded flux-cored wires were chosen for this investigation on the basis of their advantageous weld-metal deposition rates and good penetration characteristics; in addition, the use of an auxiliary shielding gas together with a flux leads to a high degree of tolerance to changes in arc parameters with minimal effect on weld quality.⁽⁹⁾

The six rutile FCAW electrodes evaluated all exhibited the above characteristics when used with the conventional d.c. power supply. Three were distinctly superior in terms of ease of bead formation, absence of spatter and bead profile in the critical 45° overhead position. All three are recent developments, with the Oerlikon SF-1 yet to be made readily available to the North American market.

The rutile slag system has a high percentage of easily ionized elements which promote stable arc and weld metal transfer characteristics. The slag is of sufficient viscosity that it forms a "dam" to support the weld metal out of position. The ingredients of



a basic slag system are not as easily ionized, to the detriment of arc stability, and the slag is more fluid, with the result that it offers little or no support to the molten weld puddle. The metal-cored wires, which produce little slag, appear, from the results obtained in the investigation, to behave similarly.

The use of pulsed current with the three selected rutile wires and the basic and metal-cored wires, failed to show the improvements in welding behavior reported by other researchers.⁽¹³⁾ In contrast to the observation of Essers and van Gompel, the arc was less concentrated with pulsed current and penetration noticeably reduced. Nevertheless, with the OTC Transistarc, the excellent welding characteristics of the rutile wires were maintained, although the operational envelope was shifted to lower wire-feed speed/mean currents. This was due to an increase in fluidity and a tendency to convex bead profiles at the higher wire-feed speeds, and to improved arc stability at the lower wire-feed speeds. The latter effect was particularly noticeable with the basic flux-cored wires, with the result that an acceptable bead profile could be obtained with the Alloy Rods T85-C1, albeit within a very narrow operating range.

Pulse parameters, other than background current, had little influence on arc and fusion characteristics. Increasing the background current



appeared to stiffen the arc, improving penetration, and reduce the fluidity of the weld puddle. However, a complete investigation could not be carried out due to the limitation of background current to 45 A maximum with the transistor regulator. The precise pulse structures arrived at for girth weld and test panel production are not, therefore, suggested as being optimum; in the subjective assessment of the operator, however, they were the best in terms of operating characteristics within the limitations of the pulsed power supplies at his disposal.

As mentioned earlier, the welding procedures developed with the three rutile wires and the one basic wire, in order to generate productivity data and prepare test panels for metallurgical evaluation, were designed to maximize productivity by adopting wire-feed speeds at the high end of the parameter envelope. Travel speeds were chosen which maintained the arc at the leading edge of the weld pool, in order to avoid slag entrapment. No attempt was made either to limit heat input or to maintain a constant heat input through the thickness of the joint.

Joint completion times for the mechanized FCAW process using the rutile consumables show significant productivity advantages, with respect to the SMAW technique, for both d.c. and pulsed operation. It



should be emphasized that these are not laboratory-measured joint completion times, but are calculated from the procedures developed for completing the 1067 mm O.D., 25 mm W.T. girth welds and applying a 70% operating factor. This figure of 70% is a conservative estimate based on field experience with the mechanized FCAW process⁽⁴⁾, in which it proved possible to complete girth welds in 1067 mm O.D., 28.8 mm W.T. pipe in three hours, exclusive of fit-up and root pass, compared with one weld every two days with the SMAW technique. Differences in joint completion times between d.c. and pulsed operation reflect, in general, the wire-feed speeds adopted, together with any discrepancies due to variations in run sequence and/or joint profile; for example, the cellulosic SMAW root and hot pass, the root especially, require considerable grinding to ensure freedom from slag entrapment, and variations in depth of grinding from joint to joint are difficult to avoid. A final point which should be mentioned in the consideration of potential productivity advantages is that all the FCAW systems studied would be capable of operating with a reduced-gap weld preparation. This was not possible in the present investigation, because of the use of SMAW root and hot passes, but could make a further, very significant contribution to improved productivity in practical applications.



The joint completion time for the girth weld produced with the basic wire is of academic interest only; the entrapped slag and lack of fusion retained in the completed weld result in the procedure being unsuitable for production applications.

The wire-feed speeds used in the bead-on-plate deposition rate experiments were the same as for fill passes in the girth weld procedures, and this is reflected in the differences in weld metal deposition rate during d.c. and pulsed current operation. Nevertheless, the deposition rates achieved with all three rutile flux-cored wires in both d.c. and pulsed modes of operation are a significant improvement over the 2 kg/h possible with the SMAW process for similar applications.

Hydrogen-assisted cracking continues to be a problem when welding thick-section structural steel, even when using high heat-input welding processes and procedures.⁽¹⁴⁾ For high integrity fabrication, only consumables depositing low hydrogen weld metal are considered; this is specified as being a maximum of 10 mL/100 g of deposited weld metal. For special structural steel and repair welding, only extra-low hydrogen consumables depositing a maximum of 5 mL/100 g of weld metal are used.⁽¹⁵⁾ All three rutile wires meet the low hydrogen designation requirement and two of them, the



Kobe DW55L and the seamless Oerlikon SF-1, are in the extra low hydrogen bracket.

The toughness properties detailed in Tables 26-29 illustrate some of the perplexities associated with the framing of specifications appropriate to thick-section steels for low temperature service, and with the selection of consumables to meet the projected demands. Extrapolation of existing requirements for North Sea service, as recently modified, would suggest that, for a design temperature of -45°C and a thickness of 25 mm, average weld-metal Charpy energy of 35 J at -55°C would be needed⁽¹⁶⁾. Despite the fact that no particular efforts had been made to optimize the welding procedures in terms of fracture toughness, all three consumables investigated met this requirement in either d.c. or pulsed welds (though only the Kobe wire did so with any degree of comfort). It cannot be concluded, however, that any of these wires are suitable for offshore structural applications at these temperatures without further work since; (i) the revised North Sea requirements refer to root-region Charpy tests, rather than the sub-surface location adopted for the present program; (ii) these requirements limit extrapolation to design temperatures in the range -20°C - $+10^{\circ}\text{C}$.



Examination of the CTOD results given in Table 29 confirms the complexity of the situation. Even the best of the three consumables, from this point of view, would not consistently meet the requirements suggested for North Sea service, extrapolated to a design temperature of -45°C (0.20 - 0.25 mm, depending on service conditions and joint location⁽¹⁶⁾). Two related difficulties appear to account for this. As has been mentioned earlier, the alloying used in these consumables to produce microstructural refinement, and ensure acceptable Charpy toughness over a range of heat inputs, results in deposits of much higher yield strength than needed to match the parent plate. This effect is compounded by the restricted heat input dictated by the all-position requirement. The high weld-metal yield strength, though beneficial in terms of the calculation of the CTOD required to achieve a specific defect tolerance, distorts the CTOD/Cv transition correlations on which the specification of Charpy energy requirements is based⁽¹⁷⁾. Specifically, the strain-rate sensitivity is expected to be lower than in lower-strength deposits, leading to a higher CTOD transition temperature than would have been anticipated on the basis of Charpy results. In addition, the combination of high yield strength and the relatively high oxygen contents (and the related inclusion populations) associated with the rutile consumables act together to reduce the CTOD levels associated with ductile tearing failure. Thus, even when "maximum-load" failure



has occurred, the actual CTOD values achieved are quite low. Clearly, the toughness which can be achieved in consumables of rutile formulation is ultimately limited by the associated oxygen contents; a reduction in weld-metal strength may lead to some improvement, but to meet requirements for low temperature, offshore service in sections significantly above 25 mm in thickness, new consumables of lower oxygen potential will have to be developed. The use of second-generation, pulsed power sources which allow pulse structure to be fully optimized may make an important contribution to the positional capability of such consumables.

As regards the relationship between microstructure and toughness in FCAW deposits, little is yet known, although the basic principles established for other arc welding processes are expected to apply. The present study does not make any significant contribution to this area, since systematic microstructural analysis was outside its scope. A comprehensive program of metallurgical study and optimization will have to be undertaken in order to develop a full understanding of the metallurgical and process factors involved.



8.0 CONCLUSIONS

- (i) Mechanized and automatic welding systems have been identified which can be used with conventional d.c. and pulsed power sources of both transformer-rectifier and motor generator type. Though some interfacing problems had to be addressed with virtually all the pulsed power source/welding system combinations studied, the feasibility of developing integrated systems suitable for both shop and site use was established. Future developments in both the flexibility of pulsed power sources and the software capabilities of automatic welding systems should further enhance the operational characteristics of such systems.
- (ii) Virtually all of the rutile-cored wires examined showed acceptable positional capabilities in the d.c. mode. Three of these wires which performed particularly well were also evaluated in the pulsed mode, and again gave excellent results; however, the operating envelope was shifted to lower wire-feed speeds (and hence, lower deposition rates).
- (iii) None of the basic or metal-cored wires gave acceptable positional capabilities in the conventional d.c. mode. With the pulsed systems available, only one of the basic consumables gave acceptable bead



profile and operating characteristics; even in that case, wire-feed speed was so low and anticipated down-time, due to heavy spatter and slag entrapment, so great that no productivity advantages, relative to SMAW with basic electrodes, could be anticipated.

- (iv) Full procedures were developed for the completion of girth welds in 1067 mm O.D., 25 mm W.T. pipe, using both d.c. and pulsed mechanized systems; welding parameters were chosen to maximize productivity while remaining suitable for completing the whole circumference in the 5G position. Joint completion times for mechanized FCAW ranged from 38% to 46% of that for a comparable shielded metal arc weld using basic electrodes; the use of a reduced-gap joint design could further improve this advantage.
- (v) Test panels for mechanical property evaluation were produced in 25 mm thick Lloyds LT60 steel using an automated system in both d.c. and pulsed modes. The welding procedures adopted were virtually identical to those developed on pipe, with the exception that the root area was back-gouged and welded with the automatic FCAW system. Given that no specific metallurgical optimization was attempted, the Charpy toughness achieved in these panels was encouraging; an average energy level of 35 J at -60°C was just achieved with all three consumables examined. On the basis of extrapolation of North Sea



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recommendations, this would be an appropriate toughness for service in the as-welded condition down to -45°C . However, CTOD values at -45°C varied from marginal to inadequate, and further metallurgical work would be needed to demonstrate the suitability of these consumables for service at this temperature. For the still-lower temperatures associated with the high Arctic, and for as-welded sections up to 40 mm (beyond which PWHT is likely to be mandatory for critical areas), additional developments in consumable and/or power source technology will have to be exploited. On the basis of current results, weld-metal yield strength and oxygen contents will have to be reduced if further, significant advances in the toughness properties of FCAW deposits are to be made.



ACKNOWLEDGEMENTS

This work was partially funded by the Physical Metallurgy Research Laboratories, CANMET, Energy Mines and Resources Canada, under Supply and Services Canada Contract OS182-00250. Lloyds LT60 material, produced under a concurrent CANMET program, was supplied by the Algoma Steel Corporation.

Thanks are due to J. Geerligs, of NOVA/Husky Research Corporation, for assistance with all electronic aspects of the project, and to CRC Automatic Welding for assistance with interfacing of the various systems and the loan of the M-200 welding machines.

Any data presented, opinions, findings, conclusions or recommendations expressed in this report are those of the authors, and do not necessarily reflect the views of CANMET.

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TABLE 1

CHEMICAL COMPOSITION OF TEST PLATE STEEL

Manufacturer	Type	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Al	Nb	V
ALGOMA	Lloyds LT60	.12	1.39	.017	.011	.28	.15	.17		.15	.027	.041	.053



TABLE 2

FLUX-CORED ARC WELDING ELECTRODES INVESTIGATED

Electrode Manufacturer	Manufacturers Designation	Flux Type	AWS Classification	Wire Diameter	Wire Construction
Alloy Rods	Dual Shield II80Ni-1	Rutile	E81T1-Ni1	1.3 mm	Abutting
Hobart	Fabco 803	Rutile	E81T1-Ni2	1.2 mm	Abutting
Kobe	DW55L	Rutile	E80T1-K2	1.2 mm	Abutting
Liquid Air	LAT-91	Rutile	E71T-1	1.2 mm	Abutting
Oerlikon	Flux-o-fil SF-1	Rutile	E71T-1	1.2 mm	Seamless
Union Carbide	Linde FC727	Rutile	E81T1-Ni2	1.2 mm	Abutting
Alloy Rods	Dual Shield T85-C1	Basic	E80T5-Ni2	1.2 mm	Abutting
Murex	Cor-o-fil B55	Basic	E70T-5	1.2 mm	Abutting
Oerlikon	Flux-o-fil 31	Basic	E70T-5	1.2 mm	Seamless
Alloy Rods	Coreweld 70	Metal	E70T-1	1.2 mm	Abutting
Murex	Cor-o-mig B57	Metal	None	1.2 mm	Abutting



TABLE 3

WELD METAL CHEMICAL COMPOSITION REQUIREMENTS FOR AWS CLASSIFICATION

Chemical Requirements for Deposited Weld Metal to AWS A5.20-79

AWS Classification	C	Mn	P	S	Si	Ni	Cr	Mo	V
E70T-1									
E71T-1	a	1.75	0.04	0.03	0.90	0.50	0.20	0.30	0.08
E70T-5									

a - amount shall be determined.

Chemical Requirements for Deposited Weld Metal to AWS A5.29-80

AWS Classification	C	Mn	P	S	Si	Ni	Cr	Mo	V
E81T1-Ni1	0.12	1.50	0.03	0.03	0.80	0.80/1.10	0.15	0.35	0.05
E81T1-Ni2	0.12	1.50	0.03	0.03	0.80	1.75/2.75	-	-	-
E80T5-Ni2	0.12	1.50	0.03	0.03	0.80	1.75/2.75	-	-	-
E80T1-K2	0.15	0.50/1.75	0.03	0.03	0.80	1.00/2.00	0.15	0.35	0.05



TABLE 4

WELD METAL MECHANICAL PROPERTY REQUIREMENTS FOR AWS CLASSIFICATION

Mechanical Property Requirements to AWS A5.20-79				
AWS Classification	Tensile Strength MPa	Yield Strength MPa	Percent Elongation in 50 mm	Cv Impact J
E70T-1	497	414	22	27 at -18°C
E71T-1				
E70T-5	497	414	22	27 at -29°C

Mechanical Property Requirements to AWS A5.29-80				
AWS Classification	Tensile Strength MPa	Yield Strength MPa	Percent Elongation in 50 mm	Cv Impact J
E81T1-Ni1	550 to 690	470	19	27 at -30°C
E81T1-Ni2	550 to 690	470	19	27 at -40°C
E80T5-Ni2	550 to 690	470	19	27 at -60°C
E80T1-K2	550 to 690	470	19	27 at -30°C



TABLE 5
RANGE OF WELDING PARAMETERS INVESTIGATED

	Arc Voltage (V)	Travel Speed mm/min.	Wire Feed Speed mm/min.	Comments
1a	21	124	3560	
b			5080	
c			6350	
d			7620	
2a		140	3560	
b			5080	
c			6350	
d			7620	
3a		155	3560	
b			5080	
c			6350	
d			7620	
4a		193	3560	
b			5080	
c			6350	
d			7620	
1a	23	124	3560	
b			5080	
c			6350	
d			7620	
2a		140	3560	
b			5080	
c			6350	
d			7620	
3a		155	3560	
b			5080	
c			6350	
d			7620	
4a		193	3560	
b			5080	
c			6350	
d			7620	
1a	25	124	3560	
b			5080	
c			6350	
d			7620	
2a		140	3560	
b			5080	
c			6350	
d			7620	
3a		155	3560	
b			5080	
c			6350	
d			7620	
4a		193	3560	
b			5080	
c			6350	
d			7620	



MATERIALS QUALITY MANAGEMENT

TABLE 6

WELDING PARAMETER RANGES FOR 45° OVERHEAD WITH D.C. POWER SUPPLY

Electrode	Type	Parameter Range		Comments
		Current (A)	Voltage (V)	
Alloy Rods II80Ni-1	Rutile	190-270	21-24	Good operating characteristics.
Hobart 803	Rutile	160-210	20-23	Fair operating characteristics, tendency to slag entrapment.
Kobe DW55L	Rutile	170-250	20-23	Good operating characteristics.
Liquid Air LAT-91	Rutile	200-230	21-24	Fair operating characteristics, deeply penetrating.
Oerlikon SF-1	Rutile	180-270	20-23	Good operating characteristics.
Linde FC727	Rutile	190-230	21-23	Fair operating characteristics, sensitive to stickout.
Alloy Rods T85-C1	Basic	-	-	No acceptable bead profile.
Murex B55	Basic	-	-	No acceptable bead profile.
Oerlikon 31	Basic	-	-	No acceptable bead profile.
Alloy Rods 70	Metal	-	-	No acceptable bead profile.
Murex B57	Metal	-	-	No acceptable bead profile.



MATERIALS QUALITY MANAGEMENT

TABLE 7

WELDING PARAMETER RANGES FOR 45° OVERHEAD WITH PULSED POWER SUPPLY

Electrode	Type	Parameter Range		Comments
		Current (A)	Voltage (V)	
Alloy Rods II80Ni-1	Rutile	145-180	21-23	Good operating characteristics.
Kobe DW55L	Rutile	150-200	20-22	Good operating characteristics.
Oerlikon SF-1	Rutile	155-200	20-22	Excellent operating characteristics.
Alloy Rods T85-C1	Basic	120-150	21-23	Acceptable bead profiles at low travel speeds only.
Murex B55	Basic	-	-	No acceptable bead profiles.
Oerlikon 31	Basic	-	-	No acceptable bead profiles.
Alloy Rods 70	Metal	-	-	No acceptable bead profiles.
Murex B57	Metal	-	-	No acceptable bead profiles.



TABLE 8

OPTIMUM PULSED WELDING PARAMETERS FOR THE RUTILE WIRES

Electrode	Electrode Diameter mm	Peak Current A	Time at Peak ms	Background Current A	Frequency Hz
Alloy Rods II80Ni-1	1.4	320	5	45	90
Kobe DW55L	1.2	410	4	45	90
Oerlikon SF-1	1.2	410	4	45	90



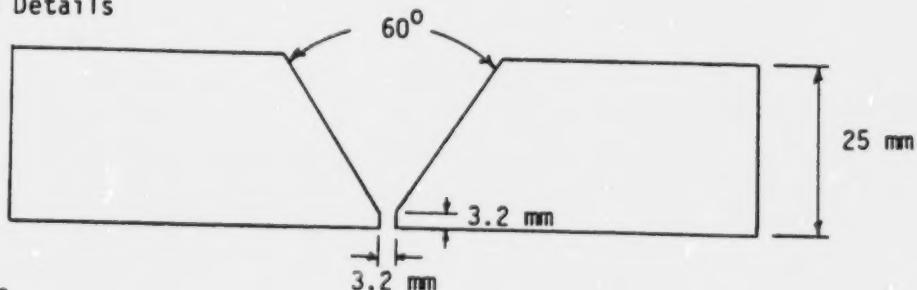
MATERIALS QUALITY MANAGEMENT

TABLE 9

GIRTH WELDING PROCEDURE WITH ALLOY RODS II80Ni-1, DIRECT CURRENT

Wire Diameter and Type: 1.4 mm Alloy Rods Dual Shield II80Ni-1
Power Source: Miller Trailblazer 550
Pipe Material: 1067 min O.D., 25 mm W.T., CSA Z245.2 Gr. 414 MPa

Joint/Preparation Details



Welding Parameters

Pass	Wire Feed Speed (mm/min)	Travel (mm/min)	Stickout (mm)	Torch Angle	Dwell L R (s)		Oscillation Velocity (mm/s)	Arc Voltage (V)	Mean Current (A)
1-2*	N/A	76	N/A	N/A	N/A	N/A	N/A	24.0	85
3	7620	203	16	+6°	0.1	0.1	31.8	22.5	275
4	7620	178	16	+6°	0.1	0.1	31.8	22.5	275
5	7620	165	16	+6°	0.1	0.1	31.8	22.5	275
6	7620	152	16	+6°	0.1	0.1	31.8	22.5	275
7	7620	127	16	+6°	0.1	0.1	31.8	23.5	260
8-9	7620	178	16	+6°	0.1	0.1	25.4	23.5	260

*SMAW -3.2 mm Ø E55010G

75A-25CO₂ Shielding Gas @ 1 m³/h
Electrode Positive Polarity

Bead Placement

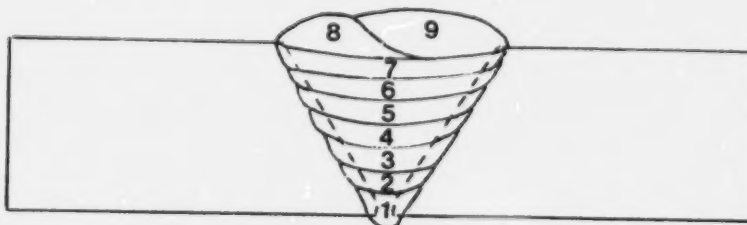


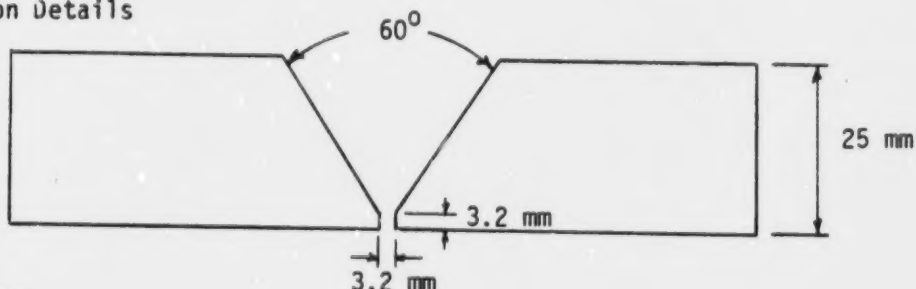


TABLE 10

GIRTH WELDING PROCEDURE WITH ALLOY RODS II80Ni-1, PULSED CURRENT

Wire Diameter and Type: 1.4 mm Alloy Rods Dual Shield II80Ni-1
 Power Source: Miller Trailblazer 550/Transistor Regulator
 Pipe Material: 1067 mm O.D., 25 mm W.T., CSA Z245.2 Gr. 414 MPa

Joint/Preparation Details



Welding Parameters

Pass	Wire Feed Speed (mm/min)	Travel (mm/min)	Stickout (mm)	Torch Angle	Dwell		Oscillation Velocity (mm/s)	Arc Voltage (V)	Mean Current (A)
					L (s)	R (s)			
1-2*	N/A	76	N/A	N/A	N/A	N/A	N/A	24.0	85
3	5461	127	16	0°	0	0	25.4	22.0	175
4	5461	152	16	0°	0	0	25.4	22.0	175
5	5461	127	16	0°	0	0	25.4	22.0	175
6	5461	102	16	0°	0.1	0.1	31.8	22.0	175
7-8	5461	127	16	0°	0.2	0.2	25.4	21.5	175

*SMAW -3.2 mm Ø E55010G

92A-8CO₂ Shielding Gas @ 1 m³/h
 Electrode Positive Polarity

Pulse Parameters

Peak Current A	Time at Peak ms	Background Current A	Frequency Hz
320	5	45	90

Bead Placement

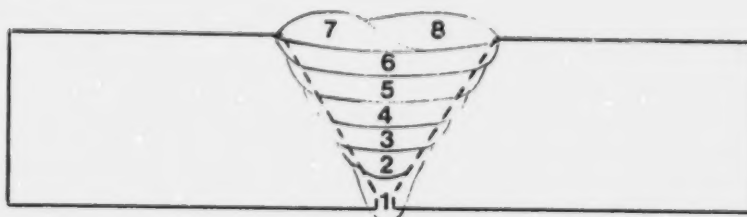


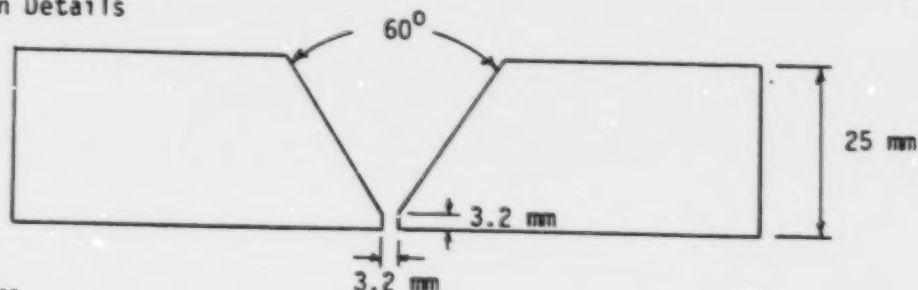


TABLE 11

GIRTH WELDING PROCEDURE WITH KOBE DW55L, DIRECT CURRENT

Wire Diameter and Type: 1.2 mm Kobe DW55L
Power Source: Miller Trailblazer 550
Pipe Material: 1067 mm O.D., 25 mm W.T., CSA Z245.2 Gr. 414 MPa

Joint/Preparation Details



Welding Parameters

Pass	Wire Feed Speed (mm/min)	Travel (mm/min)	Stickout (mm)	Torch Angle	Dwell L R (s)		Oscillation Velocity (mm/s)	Arc Voltage (V)	Mean Current (A)
1-2*	N/A	76	N/A	N/A	N/A	N/A	N/A	24.0	85
3-4	7620	178	16	0°	0	0	25.4	22.0	200
5	7620	152	16	0°	0.1	0.1	25.4	22.0	200
6	7620	127	16	0°	0.1	0.1	25.4	23.0	210
7-8	7620	152	16	0°	0.1	0.1	25.4	23.0	210
9-10	7620	127	16	0°	0.1	0.1	31.8	23.0	210

*SMAW -3.2 mm ϕ E55010G

75A-25CO₂ Shielding Gas @ 1 m³/h
Electrode Positive Polarity

Bead Placement

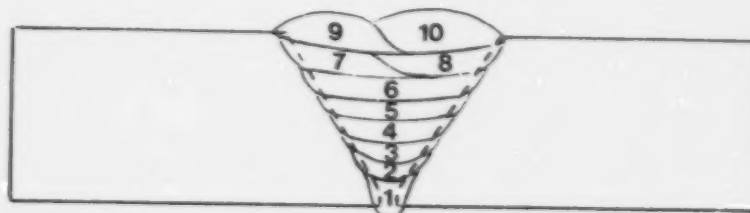


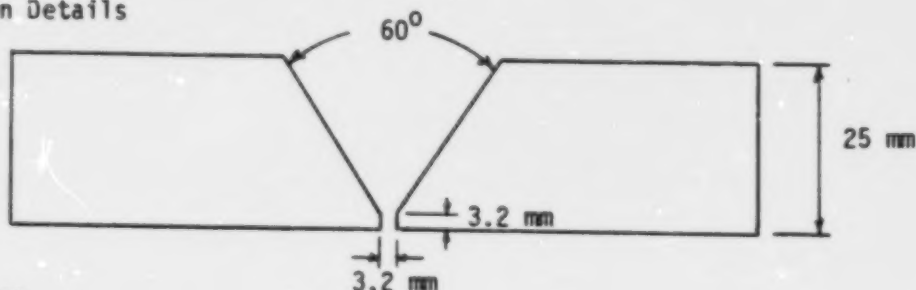


TABLE 12

GIRTH WELDING PROCEDURE WITH KOBE DW55L, PULSED CURRENT

Wire Diameter and Type: 1.2 mm Kobe DW55L
Power Source: Miller Trailblazer 550/Transistor Regulator
Pipe Material: 1067 mm O.D., 25 mm W.T., CSA Z245.2 Gr. 414 MPa

Joint/Preparation Details



Welding Parameters

Pass	Wire Feed Speed (mm/min)	Travel (mm/min)	Stickout (mm)	Torch Angle	Dwell L R (s)		Oscillation Velocity (mm/s)	Arc Voltage (V)	Mean Current (A)
1-2*	N/A	76	N/A	N/A	N/A	N/A	N/A	24.0	85
3-4	6350	165	16	+5°	0	0	31.8	20.5	180
5	6350	140	16	+5°	0	0	31.8	20.5	180
6	6350	102	16	+5°	0.2	0.2	31.8	20.5	180
7-8	5720	140	12.7	+5°	0.2	0.2	31.8	21.0	180
9-10	5720	127	12.7	+5°	0.2	0.2	31.8	21.0	180

*SMAW -3.2 mm ϕ E55010G

92A-8CO₂ Shielding Gas @ 1 m³/h
Electrode Positive Polarity

Pulse Parameters

Peak Current A	Time at Peak ms	Background Current A	Frequency Hz
410	4	45	90

Bead Placement

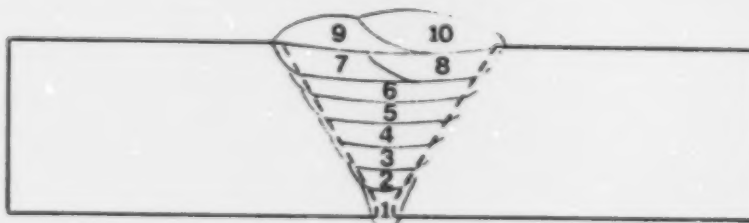


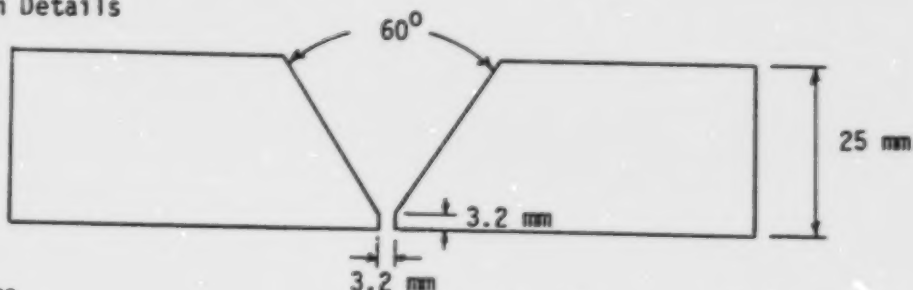


TABLE 13

GIRTH WELDING PROCEDURE WITH OERLIKON SF-1, DIRECT CURRENT

Wire Diameter and Type: 1.2 mm Oerlikon Flux-o-fil SF-1
Power Source: Miller Trailblazer 55D
Pipe Material: 1067 mm O.D., 25 mm W.T., CSA Z245.2 Gr. 414 MPa

Joint/Preparation Details



Welding Parameters

Pass	Wire Feed Speed (mm/min)	Travel (mm/min)	Stickout (mm)	Torch Angle	Dwell (s)		Oscillation Velocity (mm/s)	Arc Voltage (V)	Mean Current (A)
1-2*	N/A	76	N/A	N/A	N/A	N/A	N/A	24.0	85
3	8128	254	16	+7°	0.2	0.2	25.4	21.0	245
4	8128	229	16	+7°	0.2	0.2	31.8	21.0	245
5	8128	191	16	+7°	0.2	0.2	31.8	21.0	245
6-7	8128	191	16	+7°	0.2	0.2	31.8	22.0	240
8-9	8128	152	16	+7°	0.2	0.2	31.8	22.0	240

*SMAW -3.2 mm Ø E55010G

75A-25CO₂ Shielding Gas @ 1 m³/h
Electrode Positive Polarity

Bead Placement

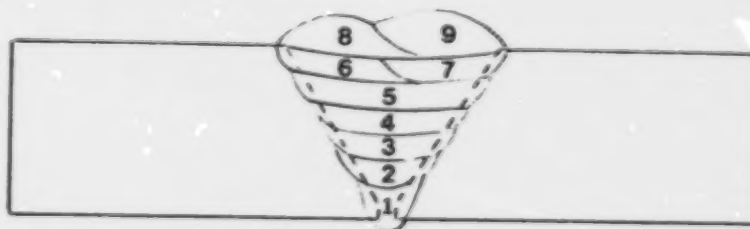


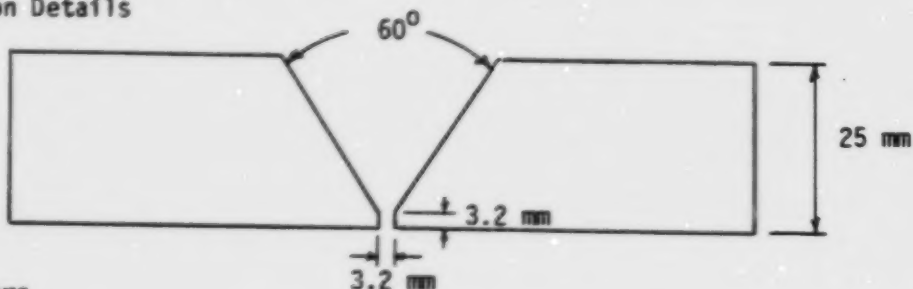


TABLE 14

GIRTH WELDING PROCEDURE WITH OERLIKON SF-1, PULSED CURRENT

Wire Diameter and Type: 1.2 mm Oerlikon Flux-o-fil SF-1
Power Source: Miller Trailblazer 550/Transistor Regulator
Pipe Material: 1067 mm O.D., 25 mm W.T., CSA Z245.2 Gr. 414 MPa

Joint/Preparation Details



Welding Parameters

Pass	Wire Feed	Travel (mm/min)	Stickout (mm)	Torch Angle	Dwell		Oscillation Velocity (mm/s)	Arc Voltage (V)	Mean Current (A)
	Speed (mm/min)				L (s)	R (s)			
1-2*	N/A	76	N/A	N/A	N/A	N/A	N/A	24.0	85
3	6350	152	16	0°	0	0	25.4	20.5	185
4	6350	127	16	0°	0	0	25.4	20.5	185
5	6350	102	16	0°	0.1	0.1	25.4	20.5	185
6-7	6350	152	16	0°	0.1	0.1	25.4	20.5	185
8-9	6350	127	16	0°	0.2	0.2	25.4	20.5	185

*SMAW -3.2 mm Ø E55010G

92A-8CO₂ Shielding Gas @ 1 m³/h
Electrode Positive Polarity

Pulse Parameters

Peak Current A	Time at Peak ms	Background Current A	Frequency Hz
410	4	45	90

Bead Placement



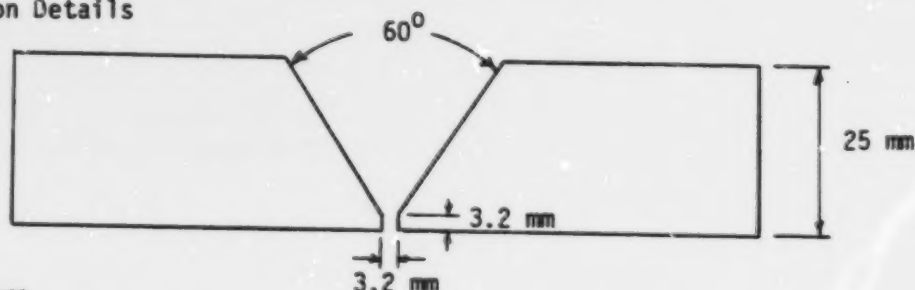


TABLE 15

GIRTH WELDING PROCEDURE WITH ALLOY RODS T85C-1, PULSED CURRENT

Wire Diameter and Type: 1.2 mm Alloy Rods T85C-1
Power Source: Lincoln DC-600/Transistor Regulator
Pipe Material: 1067 mm O.D., 25 mm W.T., CSA Z245.2 Gr. 414 MPa

Joint/Preparation Details



Welding Parameters

Pass	Wire Feed Speed (mm/min)	Travel (mm/min)	Stickout (mm)	Torch Angle	Dwell L (s)	Dwell R (s)	Oscillation Velocity (mm/s)	Arc Voltage (V)	Mean Current (A)
1-2*	N/A	76	N/A	N/A	N/A	N/A	N/A	24.0	85
3-4	5080	127	16	+7°	0.1	0.1	12.7	20.0	140
5-6	5080	114	16	+7°	0.2	0.2	12.7	20.0	140
7-12	5080	89	16	+7°	0.2	0.2	12.7	20.0	140

*SMAW -3.2 mm Ø E55010G

92A-8CO₂ Shielding Gas @ 1 m³/h
Electrode Positive Polarity

Pulse Parameters

Peak Current A	Time at Peak ms	Background Current A	Frequency Hz
410	3	45	80

Bead Placement

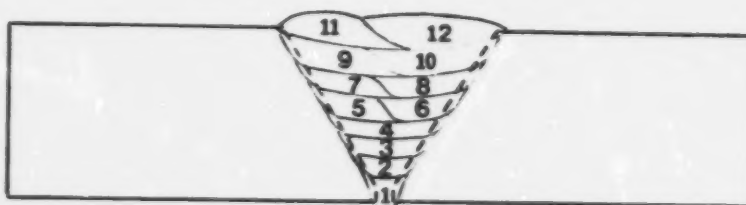


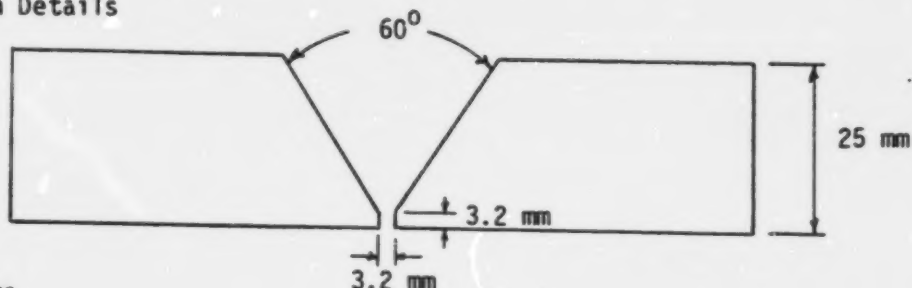


TABLE 16

GIRTH WELDING PROCEDURE WITH E55018C2 SMAW ELECTRODES

Wire Diameter and Type: 3.2 mm $\varnothing$ E55010G, 3.2, 4.0 E55018C2
Power Source: Miller Trailblazer 550
Pipe Material: 1067 mm O.D., 25 mm W.T., CSA Z245.2 Gr. 414 MPa

Joint/Preparation Details



Welding Parameters

Pass	Electrode Size & Classification	Current (A)	Arc Voltage (V)	Travel Speed (mm/min)
1-2	3.2 mm $\varnothing$ E55010G	85	24.0	76
3	3.2 mm $\varnothing$ E55018C2	120	24.5	66
4-9	4.0 mm $\varnothing$ E55018C2	135	26.0	85

Electrode Positive Polarity

Bead Placement

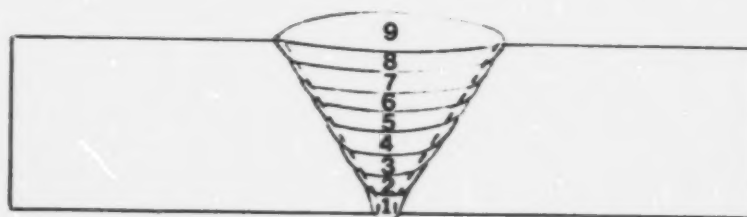




TABLE 17
WELD METAL DEPOSITION RATES

Electrode	Electrode Diameter mm	Power Supply	Wire-Feed Speed mm/min	Electrical Stickout mm	Deposition Rate kg/hr
Alloy Rods I180Ni-1	1.4	d.c.	7620	16	3.9
Alloy Rods I180Ni-1	1.4	pulsed	5461	16	2.9
Kobe DW55L	1.2	d.c.	7620	16	3.2
Kobe DW55L	1.2	pulsed	6350	16	2.7
Oerlikon SF-1	1.2	d.c.	8128	16	3.4
Oerlikon SF-1	1.2	pulsed	6350	16	2.8

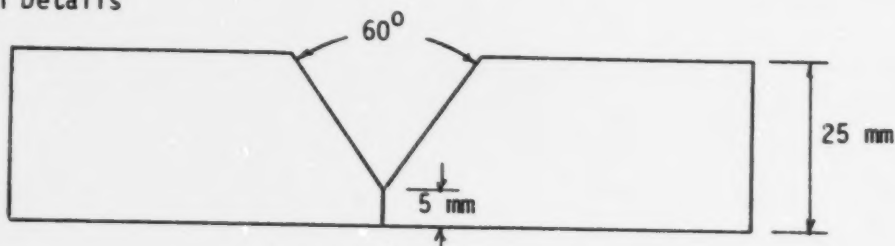


TABLE 18

TEST PANEL WELDING PROCEDURE WITH ALLOY RODS II80Ni-1, DIRECT CURRENT

Wire Diameter and Type: 1.4 mm Alloy Rods Dual Shield II80Ni-1
Power Source: Miller Trailblazer 550
Plate Thickness and Type: 25 mm Lloyds LT60

Joint/Preparation Details



Welding Parameters

Pass	Wire Feed Speed (mm/min)	Travel (mm/min)	Stickout (mm)	Torch Angle	Dwell (s)		Oscillation Velocity (mm/s)	Arc Voltage (V)	Mean Current (A)
1	5080	152	16	0°	0	0	12.7	21.0	210
2	7620	203	16	+6°	0	0	31.8	22.5	275
3	7620	178	16	+6°	0.1	0.1	31.8	22.5	275
4	7620	165	16	+6°	0.1	0.1	31.8	22.5	275
5	7620	152	16	+6°	0.1	0.1	31.8	22.5	275
6	7620	127	16	+6°	0.1	0.1	31.8	23.5	260
7	7620	102	16	+6°	0.1	0.1	31.8	23.5	260
8	7620	178	16	+6°	0	0	25.4	23.5	260

75A-25C0₂ Shielding Gas @ 1 m³/h
Electrode Positive Polarity

Bead Placement

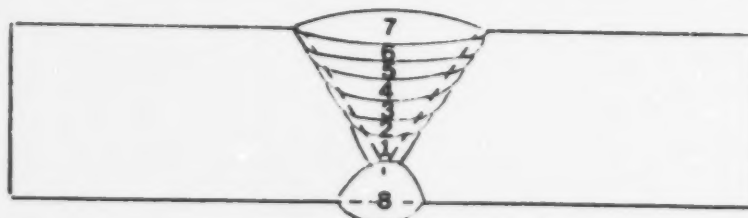


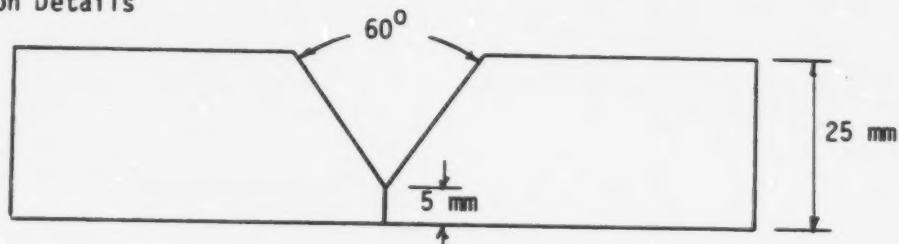


TABLE 19

TEST PANEL WELDING PROCEDURE WITH ALLOY RODS II80Ni-1, PULSED CURRENT

Wire Diameter and Type: 1.4 mm Alloy Rods Dual Shield II80Ni-1
Power Source: Miller Trailblazer 550/Transistor Regulator
Plate Thickness and Type: 25 mm Lloyds LT60

Joint/Preparation Details



Welding Parameters

Pass	Wire Feed Speed (mm/min)	Travel (mm/min)	Stickout (mm)	Torch Angle	Dwell		Oscillation Velocity (mm/s)	Arc Voltage (V)	Mean Current (A)
					L (s)	R (s)			
1	5461	127	16	0°	0	0	25.4	22.5	175
2	5461	152	16	0°	0	0	25.4	22.0	175
3	5461	127	16	0°	0	0	25.4	22.0	175
4	5461	102	16	0°	0.1	0.1	31.8	22.0	175
5	5461	64	16	0°	0.2	0.2	25.4	21.5	175
6	5461	178	16	0°	0	0	25.4	22.5	175
7	5461	127	16	0°	0	0	31.8	21.5	175

92A-8CO₂ Shielding Gas @ 1 m³/h
Electrode Positive Polarity

Pulse Parameters

Peak Current A	Time at Peak ms	Background Current A	Frequency Hz
320	5	45	90

Bead Placement

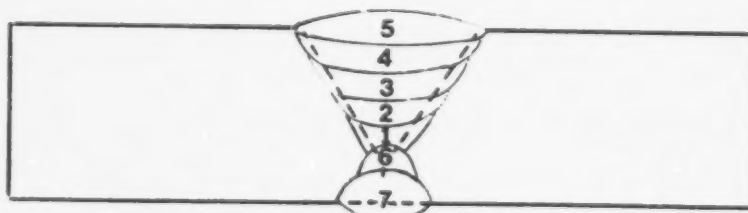


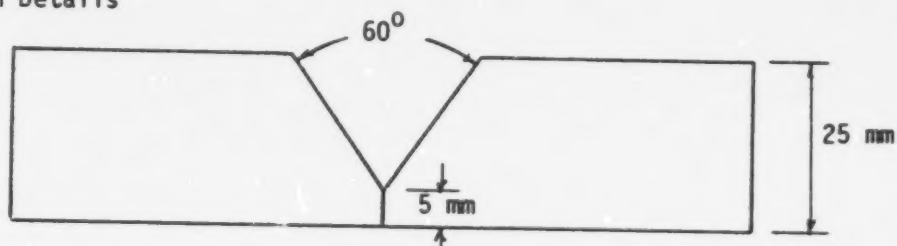


TABLE 20

TEST PANEL WELDING PROCEDURE WITH KOBE DW55L, DIRECT CURRENT

Wire Diameter and Type: 1.2 mm Kobe DW55L
Power Source: Miller Trailblazer 550
Plate Thickness and Type: 25 mm Lloyds LT60

Joint/Preparation Details



Welding Parameters

Pass	Wire Feed Speed (mm/min)	Travel (mm/min)	Stickout (mm)	Torch Angle	Dwell		Oscillation Velocity (mm/s)	Arc Voltage (V)	Mean Current (A)
					L (s)	R (s)			
1	7620	178	16	0°	0	0	25.4	22.0	200
2	7620	178	16	0°	0	0	25.4	22.0	200
3	7620	152	16	0°	0	0	25.4	22.0	200
4	7620	152	16	0°	0.1	0.1	31.8	23.0	210
5	7620	152	16	0°	0.1	0.1	31.8	23.0	210
6	7620	152	16	0°	0.1	0.1	31.8	23.0	210
7	7620	178	16	0°	0.1	0.1	31.8	23.0	210
8	7620	203	16	0°	0.1	0.1	25.4	23.0	210
9	7620	152	16	0°	0.2	0.2	25.4	23.0	210

75A-25CO₂ Shielding Gas @ 1 m³/h
Electrode Positive Polarity

Bead Placement

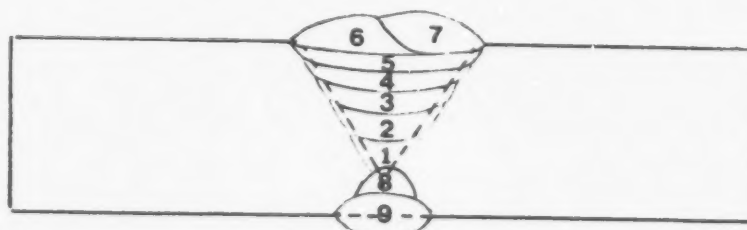


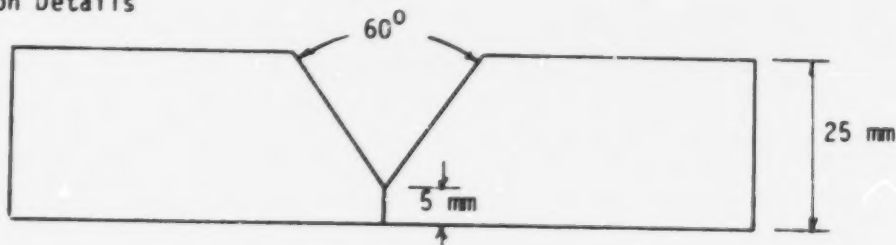


TABLE 21

TEST PANEL WELDING PROCEDURE WITH KOBE DW55L, PULSED CURRENT

Wire Diameter and Type: 1.2 mm Kobe DW55L
Power Source: Miller Trailblazer 550/Transistor Regulator
Plate Thickness and Type: 25 mm Lloyds LT6U

Joint/Preparation Details



Welding Parameters

Pass	Wire Feed Speed (mm/min)	Travel (mm/min)	Stickout (mm)	Torch Angle	Dwell		Oscillation Velocity (mm/s)	Arc Voltage (V)	Mean Current (A)
					L (s)	R (s)			
1	6350	165	16	0°	0.2	0.2	25.4	20.5	180
2	6350	165	16	0°	0.2	0.2	25.4	20.5	180
3	6350	140	16	+5°	0	0	31.8	20.5	180
4	6350	102	16	+5°	0	0	31.8	20.5	180
5	5720	127	12.7	+5°	0.2	0	31.8	21.0	180
6	5720	127	12.7	+5°	0	0.2	31.8	21.0	180
7	5720	127	12.7	+5°	0	0.2	31.8	21.0	180
8	5720	102	12.7	+5°	0.2	0	31.8	21.0	180
9	5720	203	12.7	0°	0	0	31.8	21.0	180
10	5720	165	12.7	0°	0	0	31.8	21.0	180
11	5720	114	12.7	0°	0.2	0.2	25.4	21.0	180

92A-8CO₂ Shielding Gas @ 1 m³/h

Electrode Positive Polarity

Pulse Parameters

Peak Current A	Time at Peak ms	Background Current A	Frequency Hz
410	4	45	90

Bead Placement

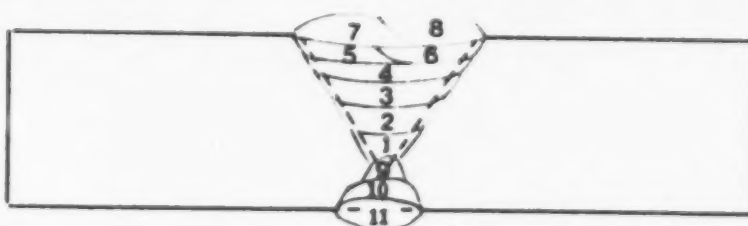


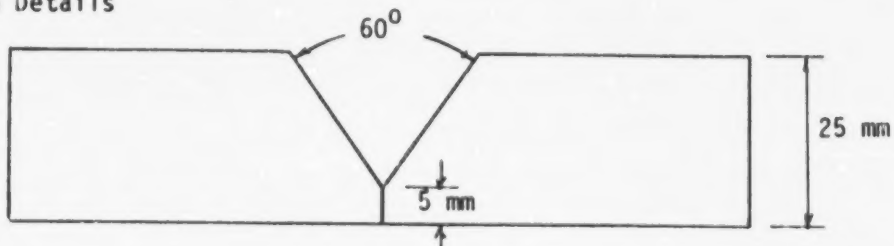


TABLE 22

TEST PANEL WELDING PROCEDURE WITH OERLIKON SF-1, DIRECT CURRENT

Wire Diameter and Type: 1.2 mm Oerlikon Flux-o-fil SF-1
Power Source: Miller Trailblazer 550
Plate Thickness and Type: 25 mm Lloyds LT60

Joint/Preparation Details



Welding Parameters

Pass	Wire Feed Speed (mm/min)	Travel (mm/min)	Stickout (mm)	Torch Angle	Dwell		Oscillation Velocity (mm/s)	Arc Voltage (V)	Mean Current (A)
					L (s)	R (s)			
1	8128	254	19	+7°	0	0	25.4	22.0	235
2	8128	254	16	+7°	0	0	25.4	21.5	245
3	8128	229	16	+7°	0.2	0.2	31.8	21.5	245
4	8128	191	16	+7°	0.2	0.2	31.8	21.0	240
5	8128	152	16	+7°	0.2	0.2	31.8	22.0	240
6	8128	127	16	+7°	0.2	0.2	31.8	22.0	240
7	8128	305	16	+7°	0	0	31.8	22.5	250
8	8128	280	16	+7°	0	0	31.8	22.0	250
9	8128	152	16	+7°	0.2	0.2	31.8	22.0	250

75A-25CO₂ Shielding Gas @ 1 m³/h
Electrode Positive Polarity

Bead Placement

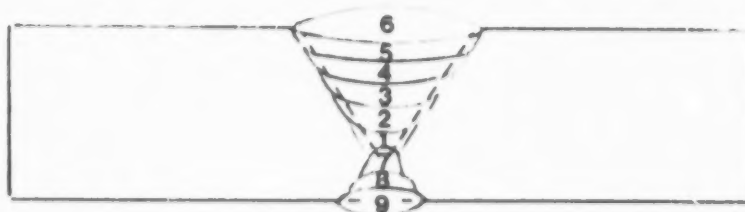


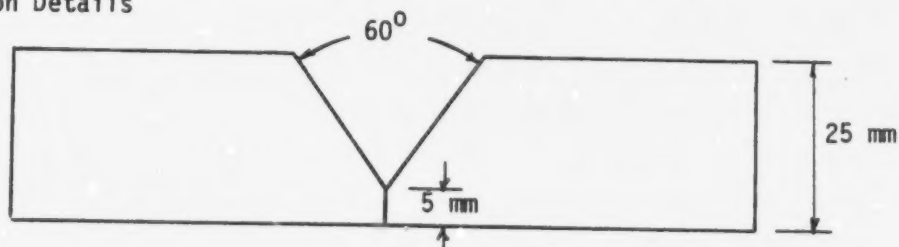


TABLE 23

TEST PANEL WELDING PROCEDURE WITH OERLIKON SF-1, PULSED CURRENT

Wire Diameter and Type: 1.2 mm Oerlikon Flux-o-fil SF-1
Power Source: Miller Trailblazer 550/Transistor Regulator
Plate Thickness and Type: 25 mm Lloyds LT60

Joint/Preparation Details



Welding Parameters

Pass	Wire Feed Speed (mm/min)	Travel (mm/min)	Stickout (mm)	Torch Angle	Dwell L (s)	Dwell R (s)	Oscillation Velocity (mm/s)	Arc Voltage (V)	Mean Current (A)
1	6350	191	16	0°	0	0	25.4	20.0	186
2	6350	152	16	0°	0.1	0.1	25.4	20.5	186
3	6350	127	16	0°	0.1	0.1	25.4	20.5	186
4	6350	102	16	0°	0.2	0.2	31.8	20.5	186
5	6350	152	16	0°	0.2	0	25.4	20.5	186
6	6350	152	16	0°	0	0.2	25.4	20.5	186
7	6350	178	16	0°	0	0	25.4	20.0	186
8	6350	140	16	0°	0.2	0.2	25.4	20.0	186

92A-8CO₂ Shielding Gas @ 1 m³/h
Electrode Positive Polarity

Pulse Parameters

Peak Current A	Time at Peak ms	Background Current A	Frequency Hz
410	4	45	90

Bead Placement

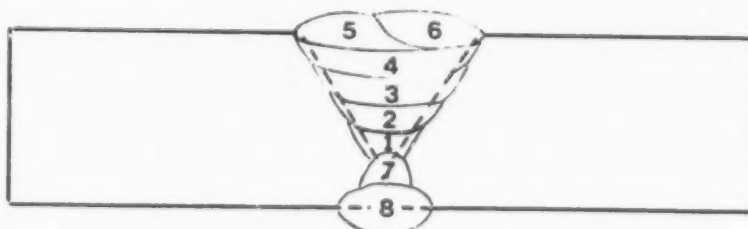




TABLE 24

WELD METAL CHEMICAL COMPOSITION

Electrode	Power Supply	C	Mn	P	S	Si	Ni	Cr	Mo	Cu	Ti	Al	V	Nb	B	O	N
Alloy Rods II80Ni-1	d.c.	.07	1.57	.007	.013	.40	.80	.05	.01	.05	.035	-	.023	.018	.0028	.067	.0044
	pulsed	.08	1.57	.006	.016	.42	.82	.06	.01	.04	.031	-	.023	.016	.0031	.056	.008
Kobe DW55L	d.c.	.05	1.48	.014	.012	.38	1.36	.08	.02	.03	.079	-	.021	.017	.0017	.059	.0043
	pulsed	.05	1.53	.014	.010	.41	1.40	.08	.02	.03	.079	-	.022	.020	.0017	.041	.0032
Oerlikon SF-1	d.c.	.07	1.66	.015	.011	.52	.04	.07	.01	.21	.054	-	.022	.015	.003	.088	.008
	pulsed	.08	1.62	.039	.011	.49	.04	.06	.01	.22	.054	-	.019	.012	.0032	.067	.006

TABLE 25
ALL-WELD-METAL TENSILE PROPERTIES

Electrode	Power Supply	YS MPa	UTS MPa	Elong. %	RA %
Alloy Rods II80Ni-1	d.c.	629 633	697 706	27 27	62 64
Alloy Rods II80Ni-1	pulsed	642 677	717 737	25 22	60 60
Kobe DW55L	d.c.	694 703	748 746	22 21	61 60
Kobe DW55L	pulsed	651 704	748 762	11 ¹ 17 ¹	32 58
Oerlikon SF-1	d.c.	708 687	757 737	19 20	49 51
Oerlikon SF-1	pulsed	699 696	758 761	18 15 ²	50 48

1. Slag defect.
2. Failed at end of gauge-length.



TABLE 26

CHARPY IMPACT TEST RESULTS FOR ALLOY RODS II80Ni-1

Temperature °C	Direct Current		Pulsed Current	
	Cv Energy J	Shear Area %	Cv Energy J	Shear Area %
0	90	95	89	95
0	91	95	87	95
0	83	95	93	95
-20	76	75	81	90
-20	76	70	78	85
-20	76	75	82	85
-40	58	60	56	60
-40	47	50	54	60
-40	47	55	58	60
-60	36	40	41	45
-60	30	35	40	45
-60	34	35	41	40
-80	15	25	18	20
-80	19	20	25	30
-80	22	20	26	35



TABLE 27

CHARPY IMPACT TEST RESULTS FOR KOBE DW55L

Temperature °C	Direct Current		Pulsed Current	
	Cv Energy J	Shear Area %	Cv Energy J	Shear Area %
0	85	100	90	100
0	87	100	88	100
0	83	100	87	100
-20	80	100	79	90
-20	80	95	79	90
-20	75	100	70	75
-40	73	80	65	65
-40	76	95	64	65
-40	71	90	60	60
-60	53	55	50	50
-60	59	65	47	55
-60	51	40	58	60
-80	42	30	36	30
-80	40	30	28	30
-80	44	35	29	25



TABLE 28

CHARPY IMPACT TEST RESULTS FOR OERLIKON SF-1

Temperature °C	Direct Current		Pulsed Current	
	Cv Energy J	Shear Area %	Cv Energy J	Shear Area %
0	60	100	56	95
0	57	100	58	95
0	62	100	56	95
-20	57	95	53	90
-20	58	100	51	90
-20	56	95	50	85
-40	49	90	45	75
-40	52	90	41	70
-40	51	90	41	60
-60	41	62	29	40
-60	34	60	27	35
-60	33	40	31	40
-80	22	30	17	15
-80	26	40	11	10
-80	25	35	16	15



TABLE 29
CTOD VALUES AT -45°C

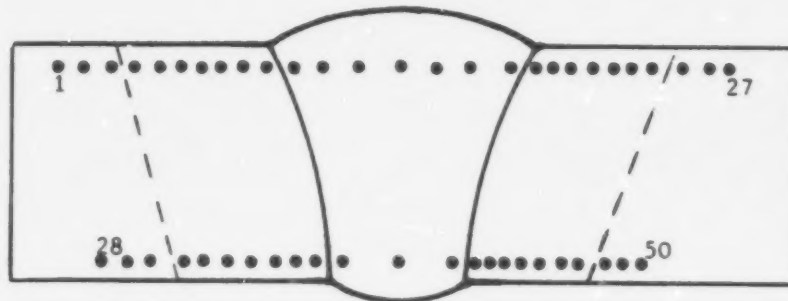
Electrode	Power Supply	CTOD at -45°C mm
Alloy Rods II80Ni-1	d.c.	0.04 (δ_c), 0.04 (δ_c), 0.03 (δ_c)
Alloy Rods II80Ni-1	pulsed	0.07 (δ_c), 0.04 (δ_c), 0.07 (δ_c)
Kobe DW55L	d.c.	0.17 (δ_m), 0.18 (δ_m), -
Kobe DW55L	pulsed	0.20 (δ_m), 0.16 (δ_m), 0.10 (δ_u)
Oerlikon SF-1	d.c.	0.05 (δ_c), 0.10 (δ_u), 0.08 (δ_u)
Oerlikon SF-1	pulsed	0.11 (δ_u), 0.07 (δ_u), 0.12 (δ_m)



TABLE 30

HARDNESS TEST RESULTS FOR ALLOY RODS II80Ni-1, DIRECT CURRENT

Type of Test: Vickers Microhardness (500 gram load, 15 sec. load time)



FG - Fine Grain
CG - Coarse Grain

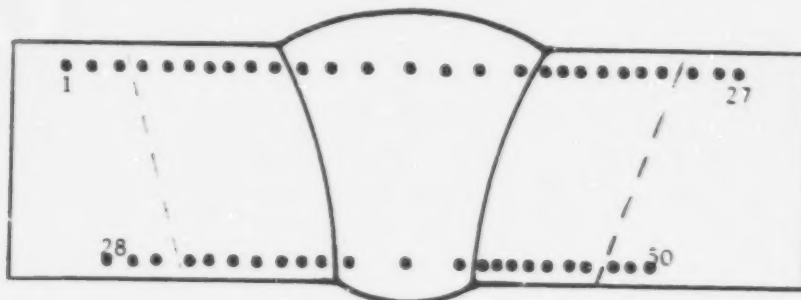
LOCATION	MICRO #			LOCATION	MICRO #		
	1 HVN	2 HVN	3 HVN		1 HVN	2 HVN	3 HVN
1. Parent Metal	176	173	180	26. Parent Metal	181	182	191
2. Parent Metal	171	169	183	27. Parent Metal	173	176	196
3. Parent Metal	186	180	174	28. Parent Metal	169	189	180
4. HAZ (FG)	190	196	175	29. Parent Metal	171	183	188
5. HAZ (FG)	193	198	199	30. Parent Metal	180	174	197
6. HAZ (FG)	209	194	192	31. HAZ (FG)	201	213	202
7. HAZ (FG)	202	197	194	32. HAZ (FG)	220	208	220
8. HAZ (CG)	219	231	215	33. HAZ (FG)	242	222	234
9. HAZ (CG)	226	238	234	34. HAZ (FG)	280	229	251
10. HAZ (CG)	244	252	230	35. HAZ (CG)	278	252	262
11. Weld Metal	222	233	231	36. HAZ (CG)	307	275	287
12. Weld Metal	238	221	218	37. HAZ (CG)	349	310	307
13. Weld Metal	232	225	216	38. Weld Metal	248	258	285
14. Weld Metal	229	222	222	39. Weld Metal	238	253	240
15. Weld Metal	231	223	220	40. Weld Metal	240	257	263
16. Weld Metal	225	229	210	41. HAZ (CG)	312	318	300
17. Weld Metal	228	240	218	42. HAZ (CG)	299	285	274
18. HAZ (CG)	230	253	241	43. HAZ (CG)	258	248	241
19. HAZ (CG)	240	245	233	44. HAZ (FG)	234	232	217
20. HAZ (CG)	253	241	249	45. HAZ (FG)	222	221	198
21. HAZ (FG)	224	239	226	46. HAZ (FG)	198	207	195
22. HAZ (FG)	206	230	218	47. HAZ (FG)	196	197	190
23. HAZ (FG)	209	224	205	48. Parent Metal	180	171	172
24. HAZ (FG)	203	197	198	49. Parent Metal	174	179	180
25. Parent Metal	190	191	200	50. Parent Metal	177	184	175



MATERIALS QUALITY MANAGEMENT

TABLE 31

HARDNESS TEST RESULTS FOR ALLOY RODS IIBON1-1, PULSED CURRENT
Type of Test: Vickers Microhardness (500 gram load, 15 sec. load time)



FG - Fine Grain
CG - Coarse Grain

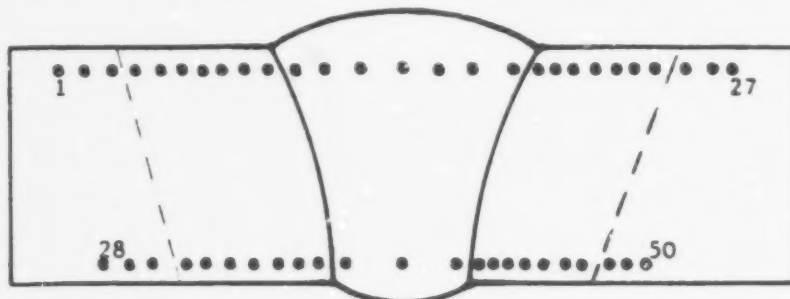
LOCATION	MICRO #			LOCATION	MICRO #		
	1 HVN	2 HVN	3 HVN		1 HVN	2 HVN	3 HVN
1. Parent Metal	173	181	180	26. Parent Metal	175	175	175
2. Parent Metal	184	175	183	27. Parent Metal	178	170	168
3. Parent Metal	188	178	174	28. Parent Metal	179	180	167
4. HAZ (FG)	200	194	175	29. Parent Metal	182	183	183
5. HAZ (FG)	204	190	199	30. Parent Metal	193	211	194
6. HAZ (FG)	221	223	207	31. HAZ (FG)	217	236	202
7. HAZ (FG)	248	210	203	32. HAZ (FG)	240	257	230
8. HAZ (CG)	253	233	249	33. HAZ (FG)	266	276	253
9. HAZ (CG)	265	240	245	34. HAZ (FG)	282	280	294
10. HAZ (CG)	255	270	240	35. HAZ (CG)	287	283	303
11. Weld Metal	231	226	242	36. HAZ (CG)	334	342	296
12. Weld Metal	238	217	228	37. HAZ (CG)	317	328	330
13. Weld Metal	226	226	223	38. Weld Metal	274	279	274
14. Weld Metal	237	227	237	39. Weld Metal	269	294	299
15. Weld Metal	230	223	237	40. Weld Metal	266	269	264
16. Weld Metal	235	219	229	41. HAZ (CG)	343	330	305
17. Weld Metal	229	229	226	42. HAZ (CG)	318	304	300
18. HAZ (CG)	249	253	244	43. HAZ (CG)	245	275	281
19. HAZ (CG)	227	255	250	44. HAZ (FG)	224	225	245
20. HAZ (CG)	246	252	233	45. HAZ (FG)	234	226	225
21. HAZ (FG)	225	242	208	46. HAZ (FG)	224	227	217
22. HAZ (FG)	202	231	198	47. HAZ (FG)	214	206	203
23. HAZ (FG)	192	216	188	48. Parent Metal	171	173	176
24. HAZ (FG)	196	201	184	49. Parent Metal	173	168	185
25. Parent Metal	187	202	181	50. Parent Metal	168	172	187



TABLE 32

HARDNESS TEST RESULTS FOR KOBE DW55L, DIRECT CURRENT

Type of Test: Vickers Microhardness (500 gram load, 15 sec. load time)



FG - Fine Grain
CG - Coarse Grain

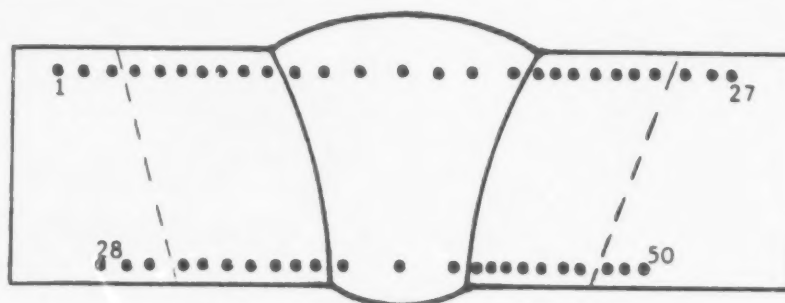
LOCATION	MICRO #			LOCATION	MICRO #		
	1 HVN	2 HVN	3 HVN		1 HVN	2 HVN	3 HVN
1. Parent Metal	172	172	174	26. Parent Metal	174	184	181
2. Parent Metal	176	170	173	27. Parent Metal	170	180	176
3. Parent Metal	185	182	194	28. Parent Metal	173	193	176
4. HAZ (FG)	207	209	211	29. Parent Metal	177	195	177
5. HAZ (FG)	229	225	216	30. Parent Metal	181	200	203
6. HAZ (FG)	237	226	236	31. HAZ (FG)	233	222	212
7. HAZ (FG)	246	258	254	32. HAZ (FG)	249	244	238
8. HAZ (CG)	280	296	283	33. HAZ (FG)	253	240	259
9. HAZ (CG)	296	307	290	34. HAZ (FG)	270	257	295
10. HAZ (CG)	287	304	334	35. HAZ (CG)	302	307	324
11. Weld Metal	248	282	297	36. HAZ (CG)	318	299	317
12. Weld Metal	271	253	270	37. HAZ (CG)	324	310	336
13. Weld Metal	266	244	275	38. Weld Metal	281	252	296
14. Weld Metal	275	282	264	39. Weld Metal	258	273	276
15. Weld Metal	271	240	269	40. Weld Metal	296	260	263
16. Weld Metal	280	280	265	41. HAZ (CG)	312	335	284
17. Weld Metal	265	267	266	42. HAZ (CG)	300	320	317
18. HAZ (CG)	285	296	293	43. HAZ (CG)	287	281	278
19. HAZ (CG)	303	297	309	44. HAZ (FG)	247	263	249
20. HAZ (CG)	275	266	290	45. HAZ (FG)	225	235	240
21. HAZ (FG)	280	253	283	46. HAZ (FG)	207	210	221
22. HAZ (FG)	241	229	241	47. HAZ (FG)	210	202	222
23. HAZ (FG)	218	221	225	48. Parent Metal	172	191	172
24. HAZ (FG)	210	213	205	49. Parent Metal	165	184	179
25. Parent Metal	179	178	168	50. Parent Metal	162	187	173



TABLE 33

HARDNESS TEST RESULTS FOR KOBE DW55L, PULSED CURRENT

Type of Test: Vickers Microhardness (500 gram load, 15 sec. load time)



FG - Fine Grain
CG - Coarse Grain

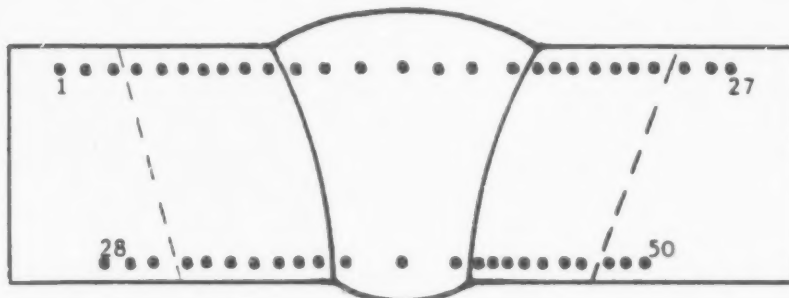
LOCATION	MICRO #			LOCATION	MICRO #		
	1 HVN	2 HVN	3 HVN		1 HVN	2 HVN	3 HVN
1. Parent Metal	182	184	175	26. Parent Metal	177	193	177
2. Parent Metal	190	186	186	27. Parent Metal	182	187	186
3. Parent Metal	179	184	181	28. Parent Metal	175	174	176
4. HAZ (FG)	197	203	262	29. Parent Metal	188	176	193
5. HAZ (FG)	217	209	280	30. Parent Metal	182	172	190
6. HAZ (FG)	228	221	253	31. HAZ (FG)	224	201	208
7. HAZ (FG)	241	247	278	32. HAZ (FG)	231	215	252
8. HAZ (CG)	245	258	285	33. HAZ (FG)	236	220	248
9. HAZ (CG)	255	243	294	34. HAZ (FG)	220	250	264
10. HAZ (CG)	261	254	325	35. HAZ (CG)	258	261	283
11. Weld Metal	300	279	316	36. HAZ (CG)	263	274	293
12. Weld Metal	319	301	285	37. HAZ (CG)	260	289	312
13. Weld Metal	280	258	296	38. Weld Metal	254	270	258
14. Weld Metal	281	250	308	39. Weld Metal	253	273	272
15. Weld Metal	267	269	302	40. Weld Metal	257	288	265
16. Weld Metal	270	257	289	41. HAZ (CG)	286	262	299
17. Weld Metal	283	309	301	42. HAZ (CG)	271	285	285
18. HAZ (CG)	291	333	272	43. HAZ (CG)	290	277	283
19. HAZ (CG)	308	308	258	44. HAZ (FG)	270	280	270
20. HAZ (CG)	289	297	295	45. HAZ (FG)	253	270	258
21. HAZ (FG)	258	289	255	46. HAZ (FG)	229	244	225
22. HAZ (FG)	232	258	234	47. HAZ (FG)	203	205	201
23. HAZ (FG)	214	231	220	48. Parent Metal	182	173	183
24. HAZ (FG)	202	224	223	49. Parent Metal	177	180	175
25. Parent Metal	173	188	189	50. Parent Metal	171	160	179



TABLE 34

HARDNESS TEST RESULTS FOR OERLIKON SF-1, DIRECT CURRENT

Type of Test: Vickers Microhardness (500 gram load, 15 sec. load time)



FG - Fine Grain
CG - Coarse Grain

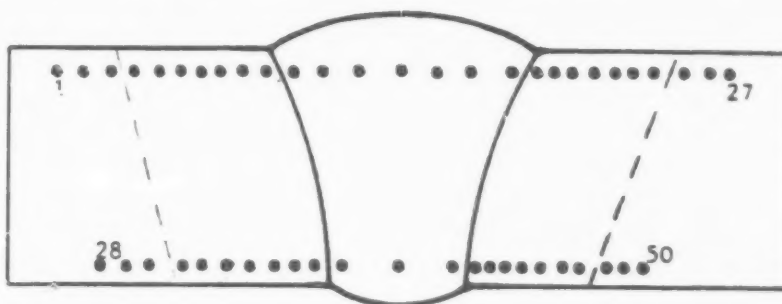
LOCATION	MICRO #			LOCATION	MICRO #		
	1 HVN	2 HVN	3 HVN		1 HVN	2 HVN	3 HVN
1. Parent Metal	176	172	174	26. Parent Metal	171	173	174
2. Parent Metal	173	181	188	27. Parent Metal	174	177	176
3. Parent Metal	176	175	182	28. Parent Metal	180	189	178
4. HAZ (FG)	213	225	217	29. Parent Metal	186	182	175
5. HAZ (FG)	215	221	231	30. Parent Metal	182	185	177
6. HAZ (FG)	253	243	248	31. HAZ (FG)	224	210	211
7. HAZ (FG)	273	271	279	32. HAZ (FG)	243	240	272
8. HAZ (CG)	278	285	266	33. HAZ (FG)	282	277	269
9. HAZ (CG)	281	283	298	34. HAZ (FG)	280	258	285
10. HAZ (CG)	310	280	312	35. HAZ (CG)	330	316	302
11. Weld Metal	268	275	260	36. HAZ (CG)	323	301	349
12. Weld Metal	244	301	252	37. HAZ (CG)	318	297	343
13. Weld Metal	258	304	269	38. Weld Metal	280	299	279
14. Weld Metal	281	289	273	39. Weld Metal	294	284	284
15. Weld Metal	258	282	267	40. Weld Metal	282	291	256
16. Weld Metal	250	270	253	41. HAZ (CG)	349	309	350
17. Weld Metal	281	285	259	42. HAZ (CG)	315	317	313
18. HAZ (CG)	300	297	300	43. HAZ (CG)	300	311	325
19. HAZ (CG)	309	289	292	44. HAZ (FG)	296	270	288
20. HAZ (CG)	267	282	264	45. HAZ (FG)	277	299	282
21. HAZ (FG)	285	270	271	46. HAZ (FG)	270	266	255
22. HAZ (FG)	257	247	249	47. HAZ (FG)	232	236	231
23. HAZ (FG)	229	233	225	48. Parent Metal	179	176	182
24. HAZ (FG)	220	213	205	49. Parent Metal	175	185	169
25. Parent Metal	168	179	169	50. Parent Metal	183	184	174



TABLE 35

HARDNESS TEST RESULTS FOR OERLIKON SF-1, PULSED CURRENT

Type of Test: Vickers Microhardness (500 gram load, 15 sec. load time)



FG - Fine Grain
CG - Coarse Grain

LOCATION	MICRO #			LOCATION	MICRO #		
	1 HVN	2 HVN	3 HVN		1 HVN	2 HVN	3 HVN
1. Parent Metal	185	176	175	26. Parent Metal	168	171	176
2. Parent Metal	178	168	180	27. Parent Metal	162	169	175
3. Parent Metal	172	178	174	28. Parent Metal	173	172	183
4. HAZ (FG)	222	219	205	29. Parent Metal	184	180	175
5. HAZ (FG)	235	234	225	30. Parent Metal	182	177	184
6. HAZ (FG)	284	240	251	31. HAZ (FG)	220	215	221
7. HAZ (FG)	280	258	255	32. HAZ (FG)	249	254	244
8. HAZ (CG)	330	294	297	33. HAZ (FG)	303	283	285
9. HAZ (CG)	318	324	322	34. HAZ (FG)	300	302	281
10. HAZ (CG)	320	343	333	35. HAZ (CG)	307	331	320
11. Weld Metal	323	303	279	36. HAZ (CG)	337	335	330
12. Weld Metal	299	285	301	37. HAZ (CG)	360	310	328
13. Weld Metal	297	273	307	38. Weld Metal	288	316	308
14. Weld Metal	300	302	318	39. Weld Metal	308	298	300
15. Weld Metal	283	318	274	40. Weld Metal	300	338	341
16. Weld Metal	312	277	317	41. HAZ (CG)	348	325	320
17. Weld Metal	289	290	294	42. HAZ (CG)	315	330	344
18. HAZ (CG)	340	313	327	43. HAZ (CG)	343	305	294
19. HAZ (CG)	350	345	316	44. HAZ (FG)	296	286	297
20. HAZ (CG)	305	317	293	45. HAZ (FG)	283	270	248
21. HAZ (FG)	283	270	269	46. HAZ (FG)	257	248	229
22. HAZ (FG)	275	282	264	47. HAZ (FG)	224	226	217
23. HAZ (FG)	242	238	256	48. Parent Metal	183	182	179
24. HAZ (FG)	210	212	217	49. Parent Metal	177	180	173
25. Parent Metal	175	178	180	50. Parent Metal	180	165	180



TABLE 36

SUMMARY OF HARDNESS RESULTS

Electrode	Power Supply	Hardness Hv 0.5 kg	
		Subsurface	Root
Alloy Rods II80Ni-1	d.c.	$\frac{210 - 240}{225}$	$\frac{238 - 285}{253}$
Alloy Rods II80Ni-1	pulsed	$\frac{217 - 242}{229}$	$\frac{264 - 299}{276}$
Kobe DW55L	d.c.	$\frac{240 - 297}{268}$	$\frac{252 - 296}{273}$
Kobe DW55L	pulsed	$\frac{250 - 319}{287}$	$\frac{253 - 288}{265}$
Oerlikon SF-1	d.c.	$\frac{244 - 305}{270}$	$\frac{256 - 299}{283}$
Oerlikon SF-1	pulsed	$\frac{273 - 323}{297}$	$\frac{285 - 341}{310}$



TABLE 37
DEPOSITED WELD METAL HYDROGEN CONTENT

Electrode	Hydrogen Content mL/100 g Deposited Metal
Alloy Rods II80Ni-1	9.9
Kobe DW55L	3.9
Oerlikon SF-1	2.0

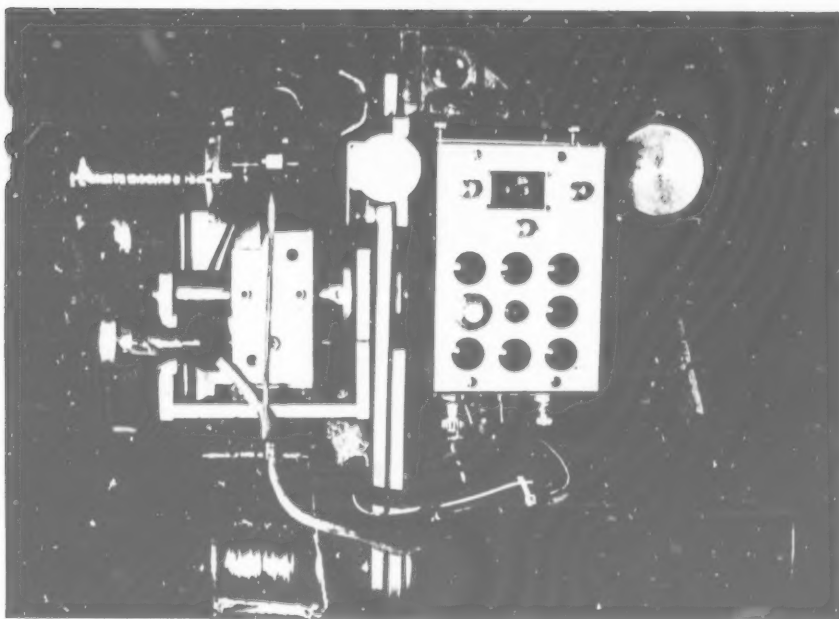
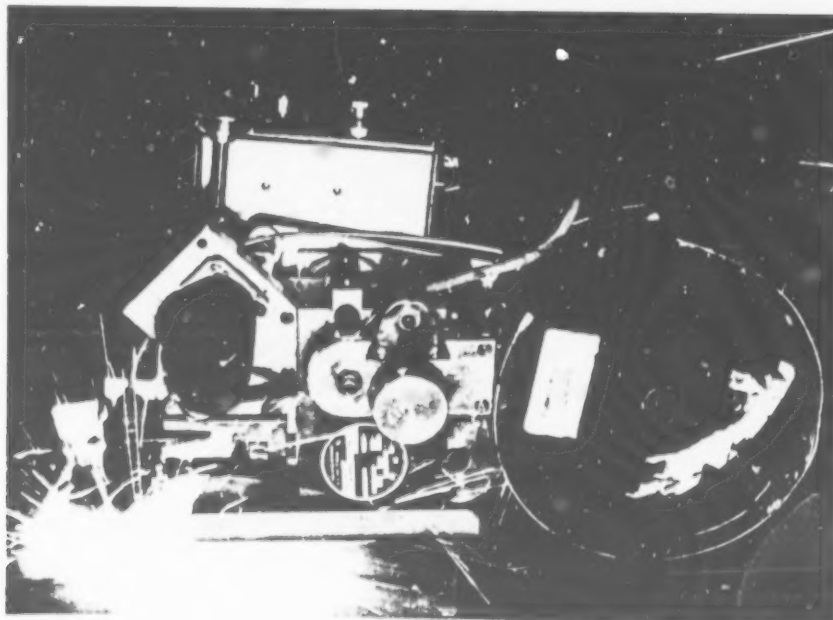
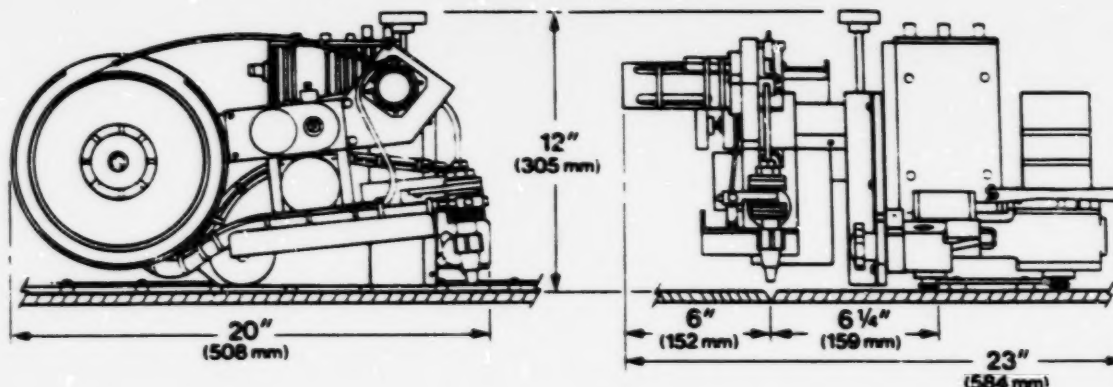


FIGURE 1

CRC Model M-200 Mechanized Welding System.



WEIGHT:

45 lbs. (20 kg.) Including
10 lb. (4.5 kg.) Wire Spool

WELDING WIRE:

Flux-Cored Wire
(Self-Shielded Or Gas-Shielded)

Solid Wire With Shielding Gas

WIRE DIAMETERS:

0.030" - 0.078" (0.8 mm - 2.0 mm)

Standard 10 lb. (4.5 kg.) Spool

WELDABLE METALS:

Any Metal Normally Welded With The
Gas-Metal-Arc Welding Process

Thickness	Pipe Diameters
3/8" (9.5 mm) or more	10" (254 mm) min.

POWER SOURCE:

Any Constant Potential Welding Power Source

WELDING POSITIONS:

All Positions - Horizontal,
Vertical, Overhead, Flat



TRACK:

Applications

For Pipe: Available In Standard Diameter
Bands Up To 60" (1,524 mm)

For Plate: Standard 10' (3 m) Flexible
Track Sections May Be Used For
Flat Or Curved Plate Surfaces

Installation

Threaded Stud Pads
Tack Welded
Epoxy Glued
Cable Tensioning

FIGURE 2

CRC M-200: Manufacturer's Data.

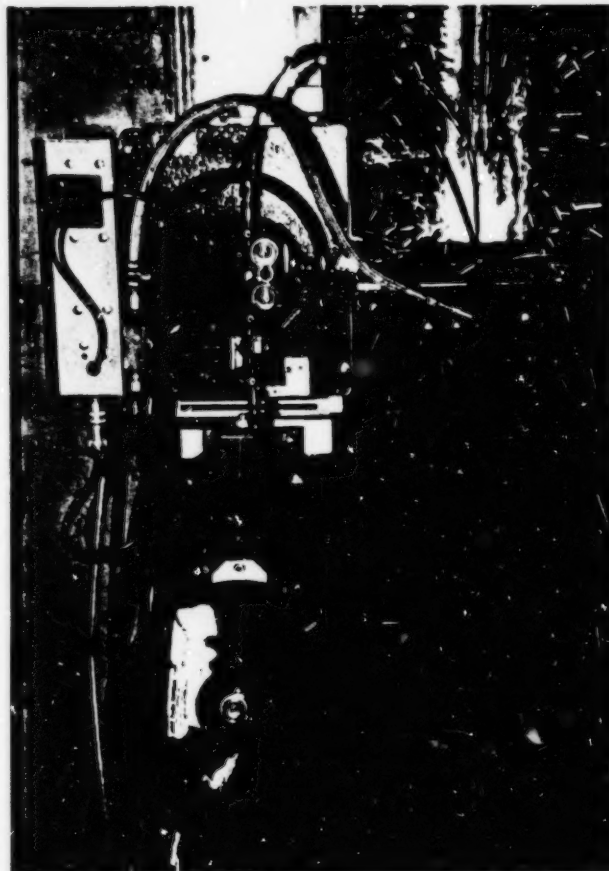
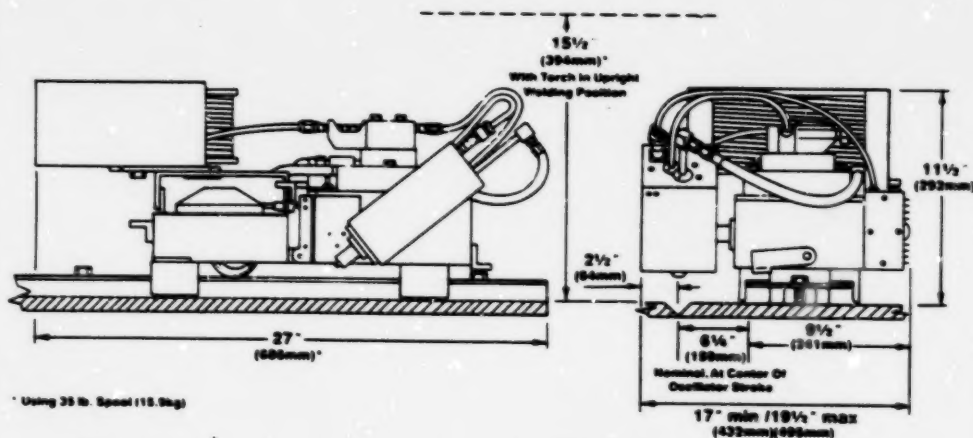


FIGURE 3

CRC Model M-1000 Automated Welding System.



* Using 35 lb. Spool (15.9kg)

WEIGHT

42 lbs. (19kg) Excluding Wire

DIMENSIONS

Height	Length	Width	Spool Size
15-1/2" (394mm)*	21" (533mm)	17" (432mm)	10 lbs. (4.5kg)
15-1/2" (394mm)*	27" (686mm)	17" (432mm)	35 lbs. (15.9kg)

* In Weld Position

WELDING WIRE

0.030" - 0.156" (0.76mm - 3.96mm)

Standard Spool Diameters Up To 35 lbs.
(15.9kg)

WIRE FEED SPEED

30 - 940 in/min (760 - 23,850mm/min)

Speed Regulation: 0.05%

TRAVEL SPEED

3.0 - 94.0 in/min (76 - 2,390mm/min)

1.5 - 47.0 in/min (38 - 1,196mm/min)

With Optional Gear Reduction

Speed Regulation: 0.05%

OSCILLATOR VELOCITY

0.15 - 75 in/min (4 - 1,900mm/min)

OSCILLATOR DISPLACEMENT

0.040" - 2.500" (1.0mm - 63.5mm)

Static Position Accuracy: $\pm 0.005"$
(0.13mm)

Positional Resolution: 0.0025" (0.06mm)

**MINIMUM SIDE WALL HEIGHT
FOR AUTOMATIC TRACKING**

0.100" (2.5mm)

TORCH-TO-WORK

Travel Range: 3.0" (76mm)

Torch Velocity: 30 in/min (760mm/min)

Static Position Accuracy: $\pm 0.005"$
(0.13mm)

Position Resolution: 0.001" (0.03mm)

Max Welding Current: 300 Amps With
Air-Cooled Torch

HEAD ANGLE

Angular Displacement: 90°

Static Position Accuracy: $\pm 0.1°$

Angular Velocity: 530°/min

Angular Resolution: 0.02°

DYNAMIC POSITION SPECIFICATION

Width Correction Range:

$\pm 1/8"$ (3.2mm)/Oscillation Sweep

Centerline Correction Range:

$\pm 1/8"$ (3.2mm)/Oscillation Sweep

C.T.W.D. Correction Range:

$\pm .100"$ (2.5mm)/Oscillation Sweep

WELDABLE METALS

Any Material Normally Welded With The
Gas-Metal-Arc Welding Process

Thickness

2" (51mm) max (Modifications Available
For Thicker Sections)

Pipe Diameters

External: 14" (356mm) min

Internal: 100" (2,540mm) min

POWER SOURCE

Any Constant Potential Welding Power
Source With Remote Voltage Control

POWER REQUIREMENTS

115 Volts AC, 5 Amps, 50/60 Hz

WELDING POSITIONS

All Positions - Horizontal, Vertical,
Overhead, Flat

TRACK

Applications

Pipe: Available in Standard Bands
Up To 60" (1,524mm) Diameter

Plate: Standard 10' (3m) Rigid Track
Sections For Flat Plate Or
Flexible Track Sections For
Curved Plate

Installation

Threaded Stud Pads

Tack Welded

Epoxy Glued

Cable Tensioning

FIGURE 4



OPERATOR

M-1000

Turn Switch On

- 1.
2. Rotates Torch To Proper Head Angle & Locates Top Of Workpiece
3. Establishes Torch-To-Work Distance
4. Feeds Correct Electrode Stickout
5. Moves Over Joint

Turn Switch Off

Turn Switch On

6. Lowers Torch Tip .150" (3.8mm)
7. Locates Inside Wall
8. Locates Outside Wall
9. Computes & Moves To Centerline
10. Locates Bottom Of Joint
11. Raises Torch .100" From Bottom
12. Locates Initial Inside Wall
13. Locates Initial Outside Wall
14. Returns To Centerline, Computes Travel, Oscillator & Wire Feed Speeds For Initial Width Using Modeled Weld Joint Configuration
15. Begins Welding, Adjusts Parameters By Real-Time, Through-The-Arc Sensing

Turn Switch Off

16. Torch Returns To Home Position

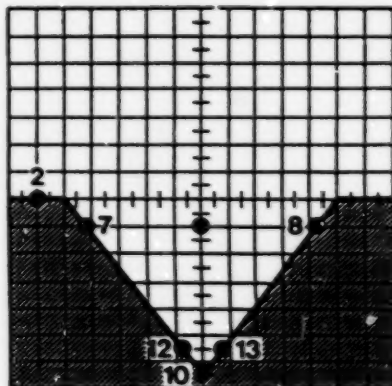
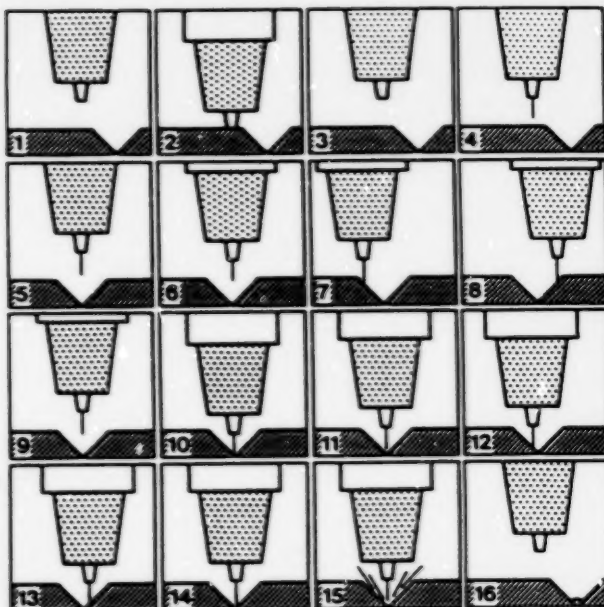


FIGURE 5

M-1000 Joint Profiling and Weld Start Sequence.



a. OTC Transistarc MM350.



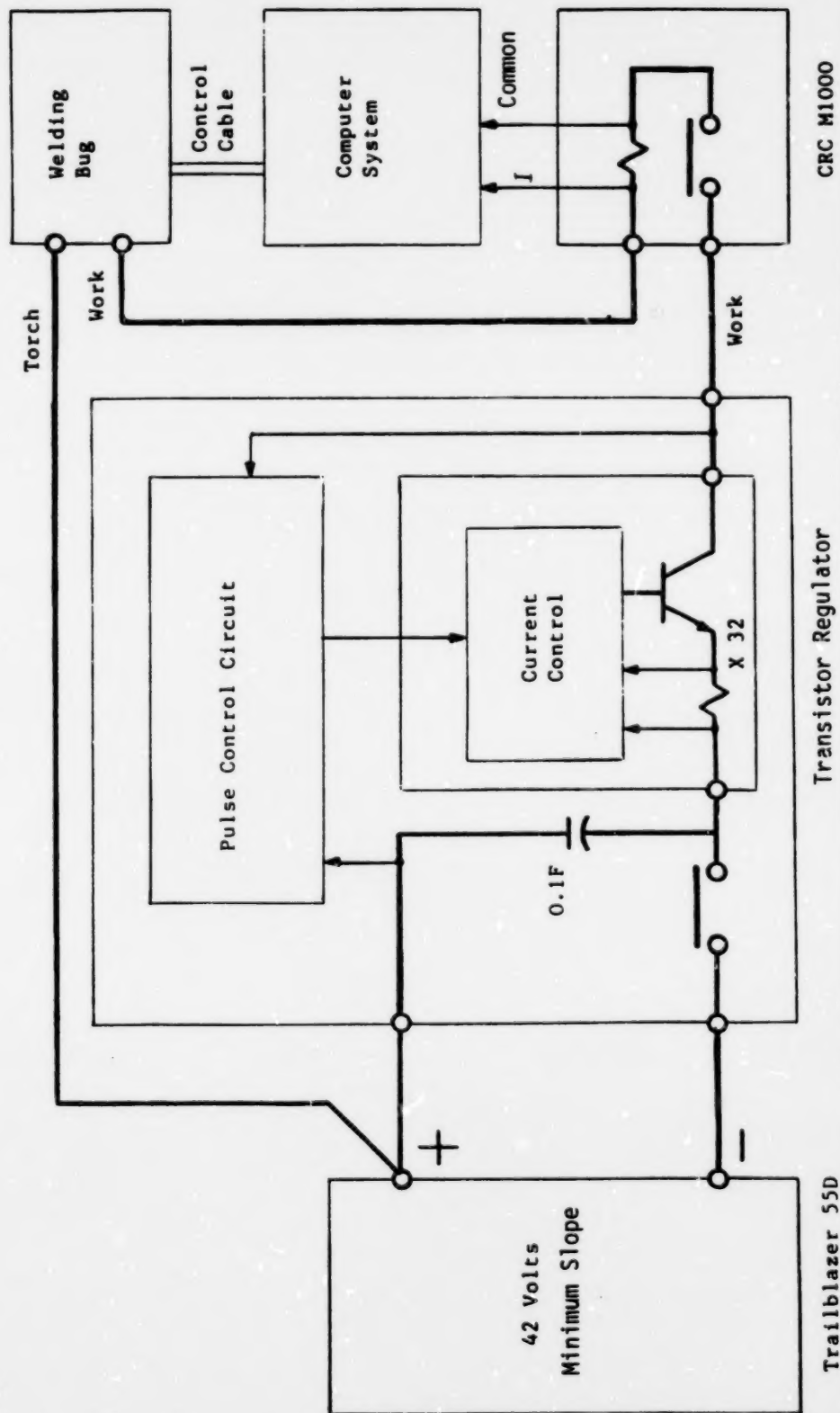
b. Transistor Power Regulator.

FIGURE 6

Pulsed Welding Power Sources.

FIGURE 7

Interconnection Diagram Showing Main Components and Welding Current Path.



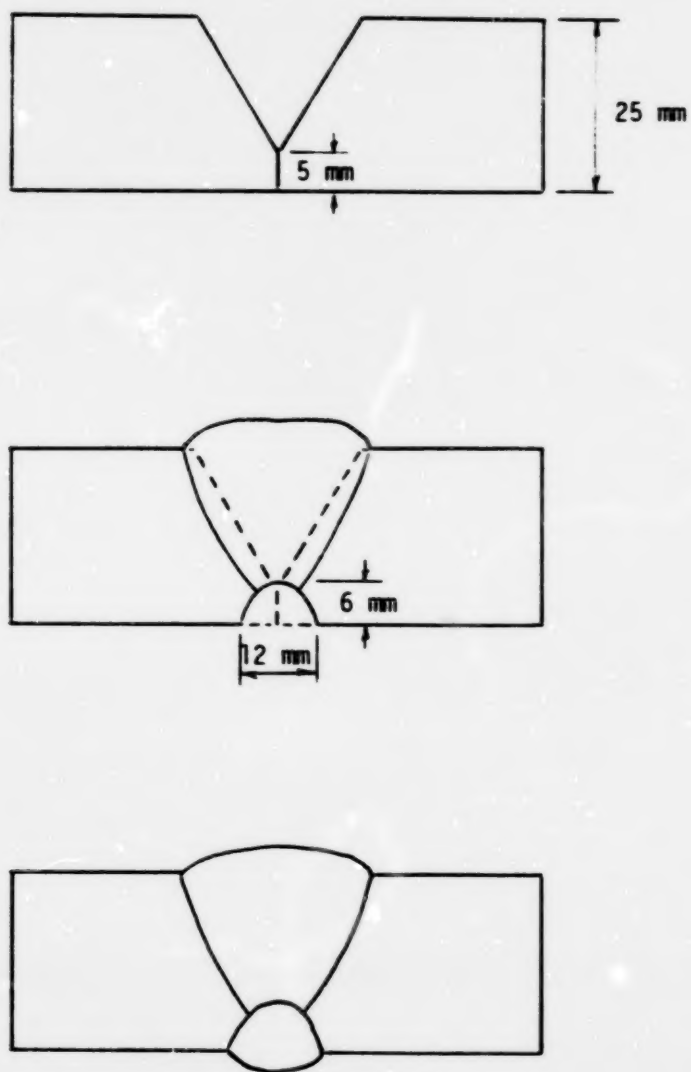


FIGURE 8

Edge Preparation and Backgouge Profile for LT 60 Test Panels.

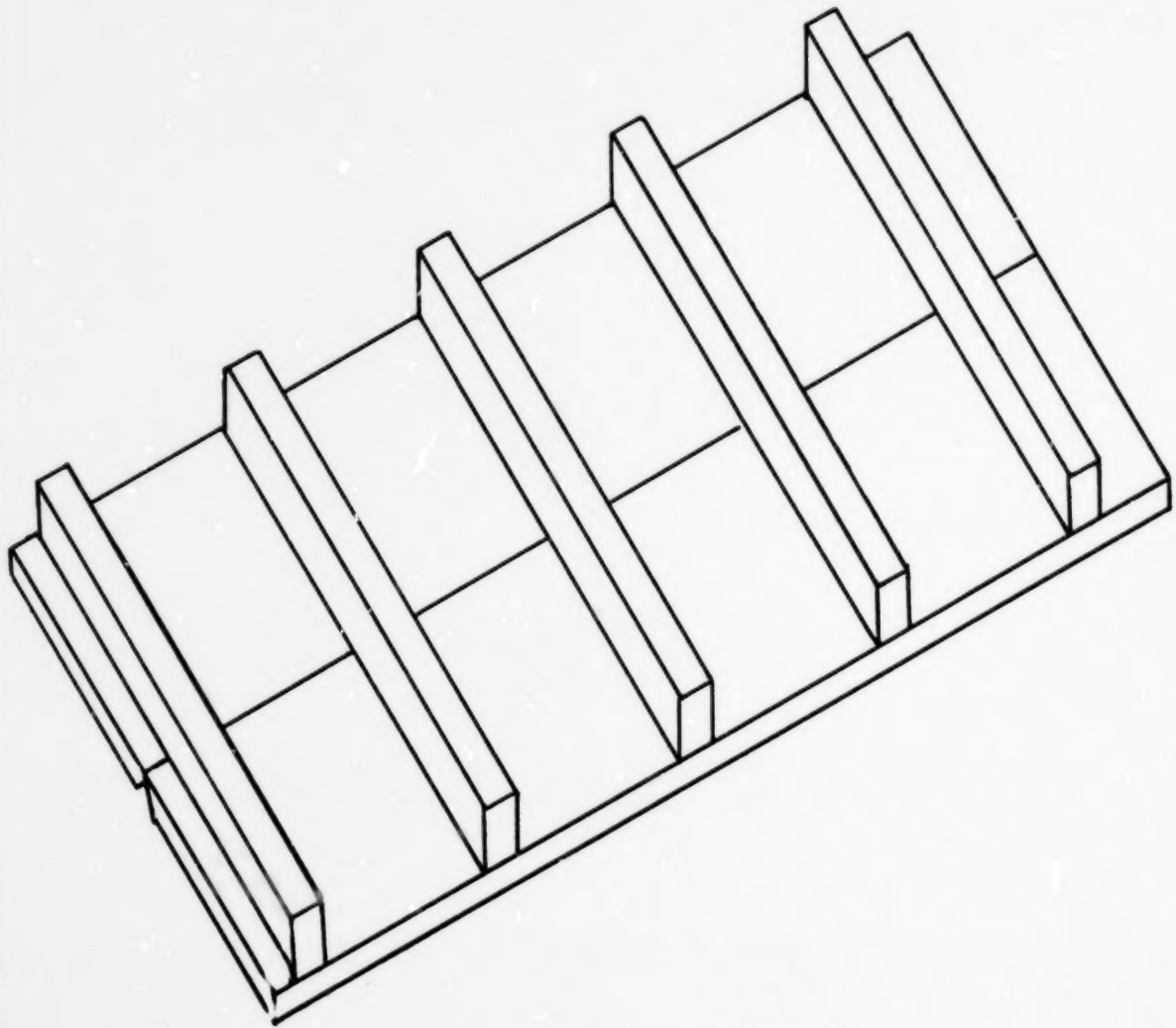


FIGURE 9

Test Panel Assembly.

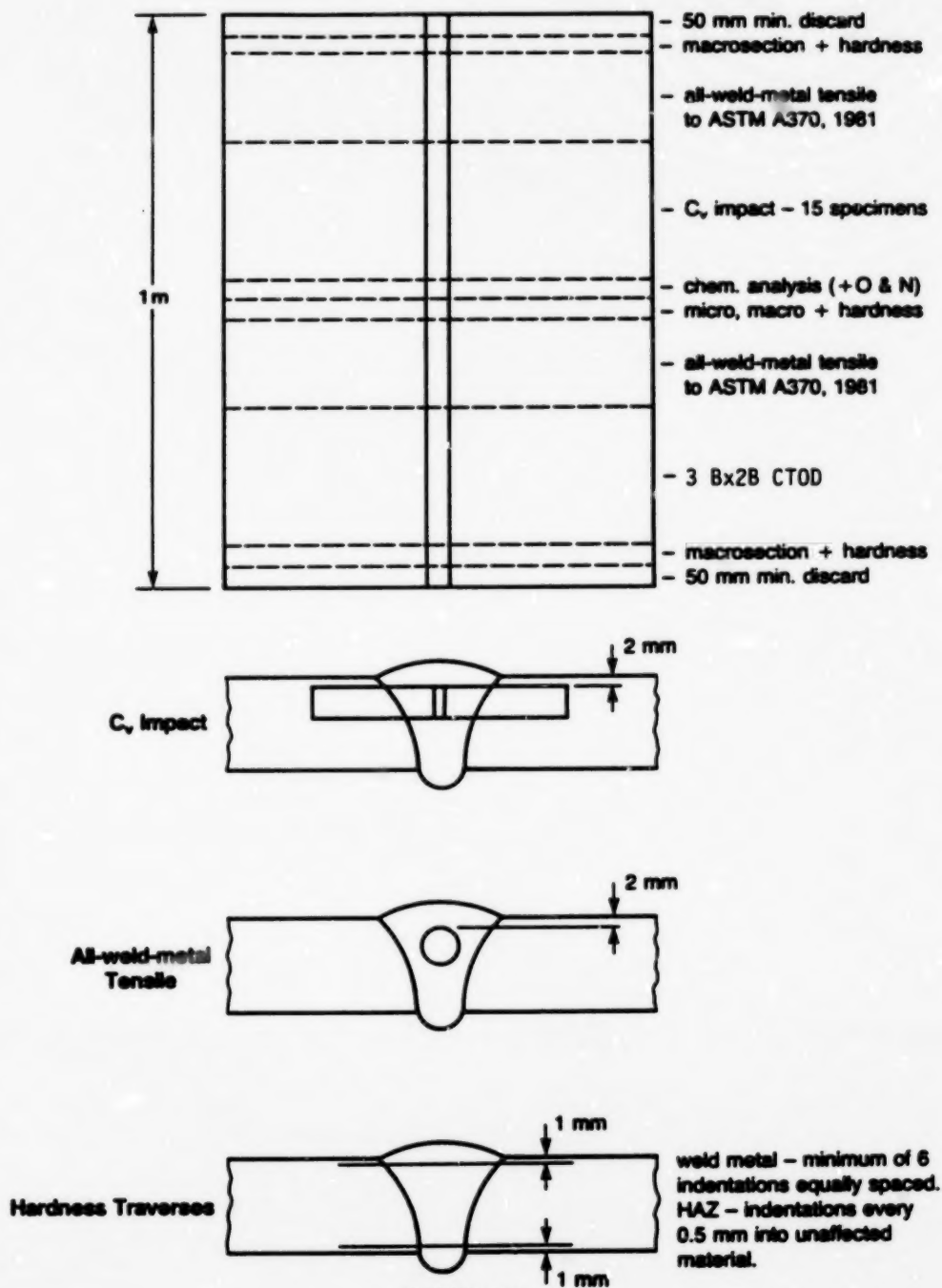
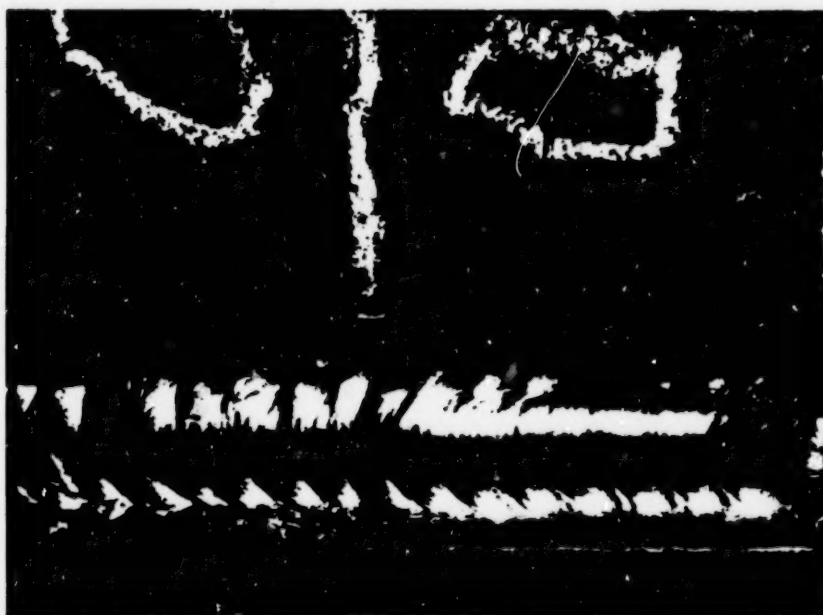


FIGURE 10

Mechanical Test Specimen Locations.



a. Typical Bead Appearance With Direct Current.



b. T85-C1 With Optimum Pulsed Welding Conditions.

FIGURE 11

Bead Appearance of Basic FCAW Deposits in 45° Overhead Position.

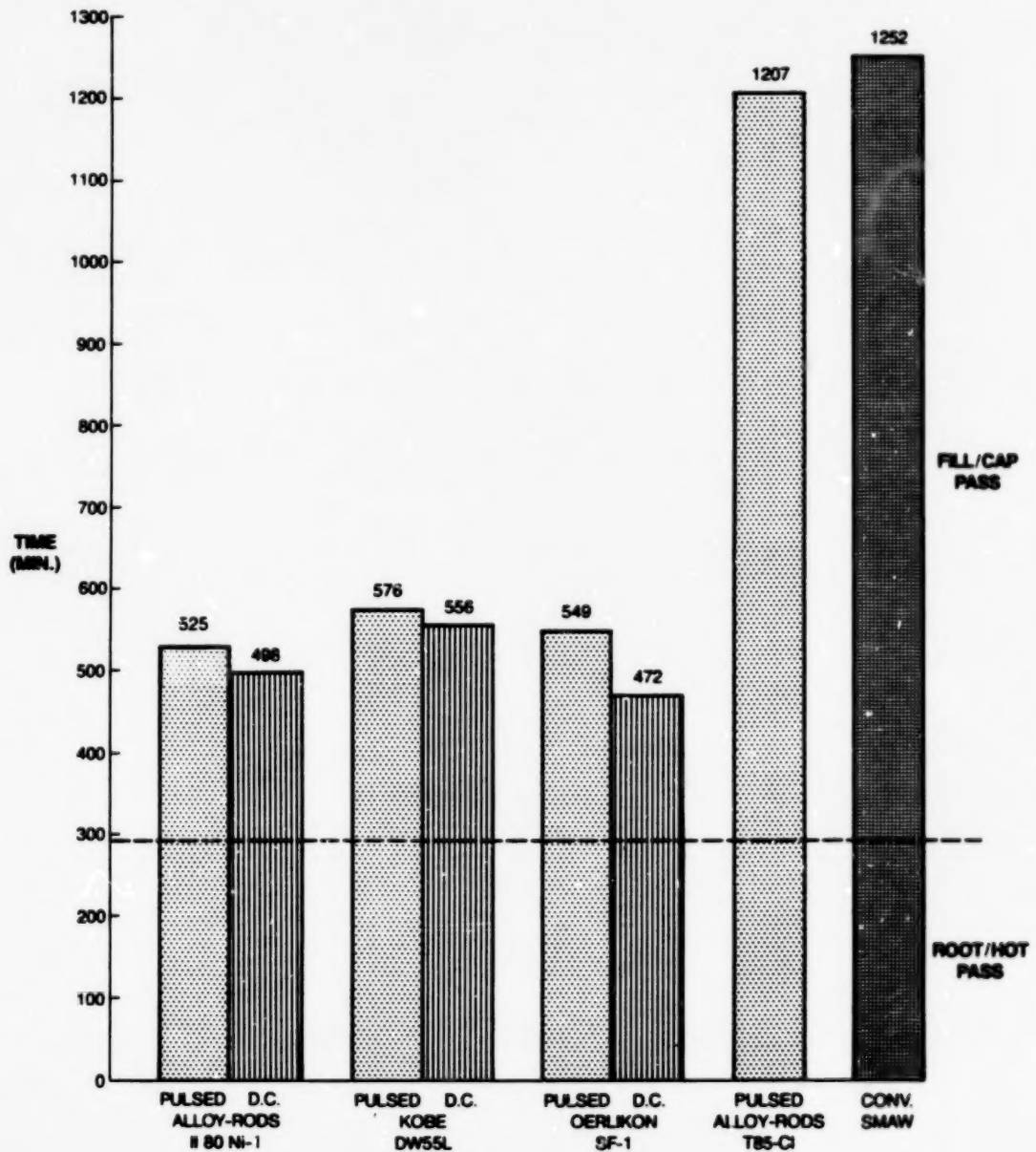


FIGURE 12

Joint completion times for girth welds in
1067 mm O.D., 25 mm W.T. pipe.

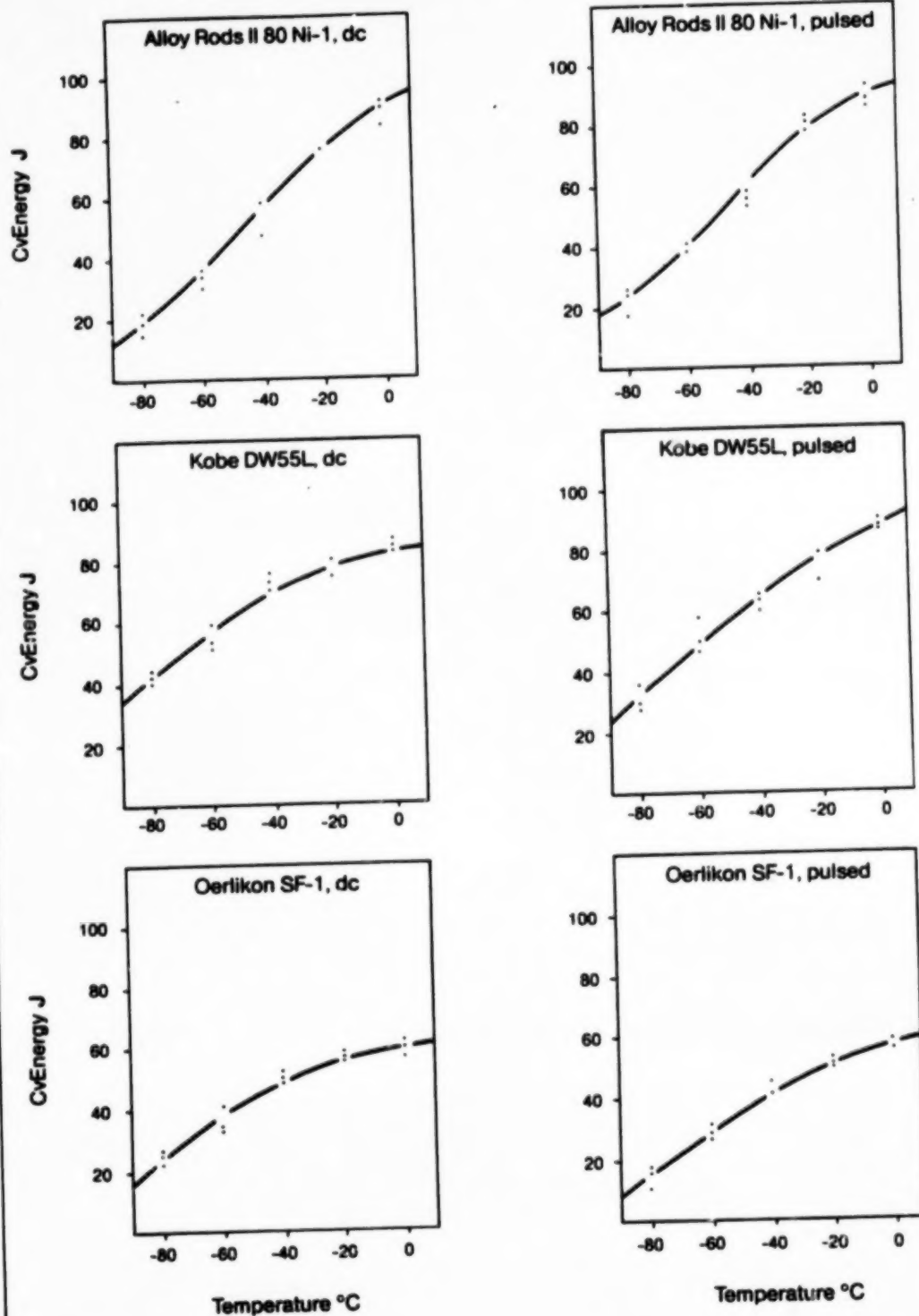
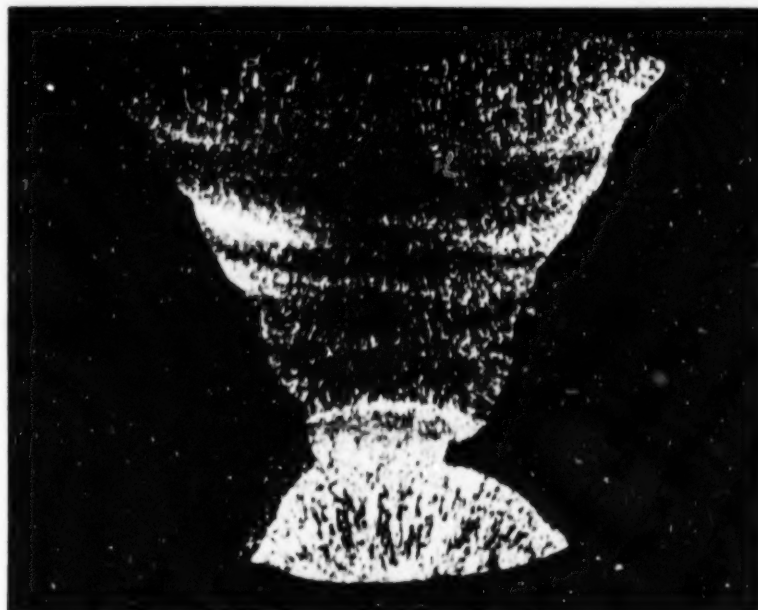


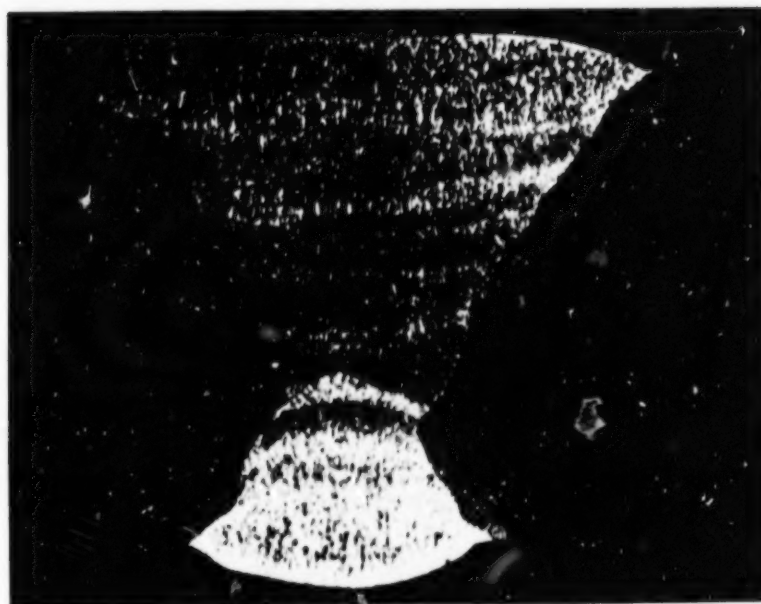
FIGURE 13

Cv energy transition curves.



a. Direct Current

x2.5

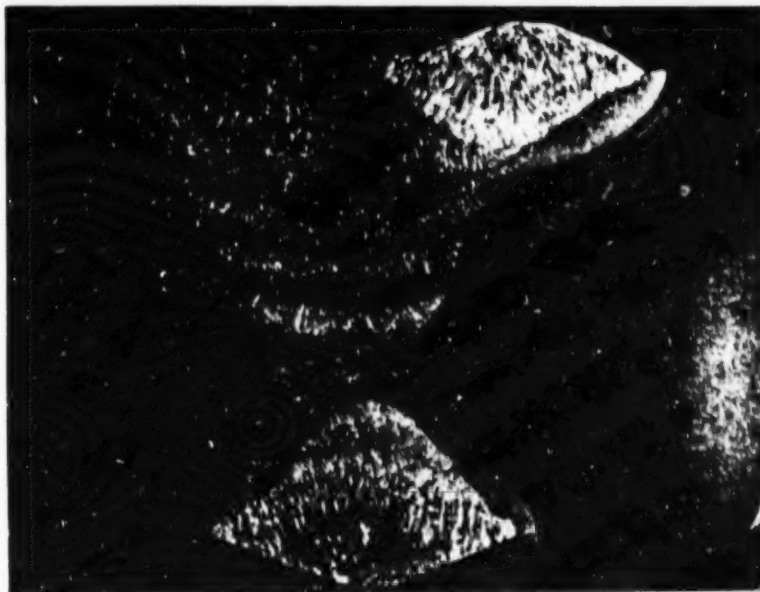


b. Pulsed Current

x2.5

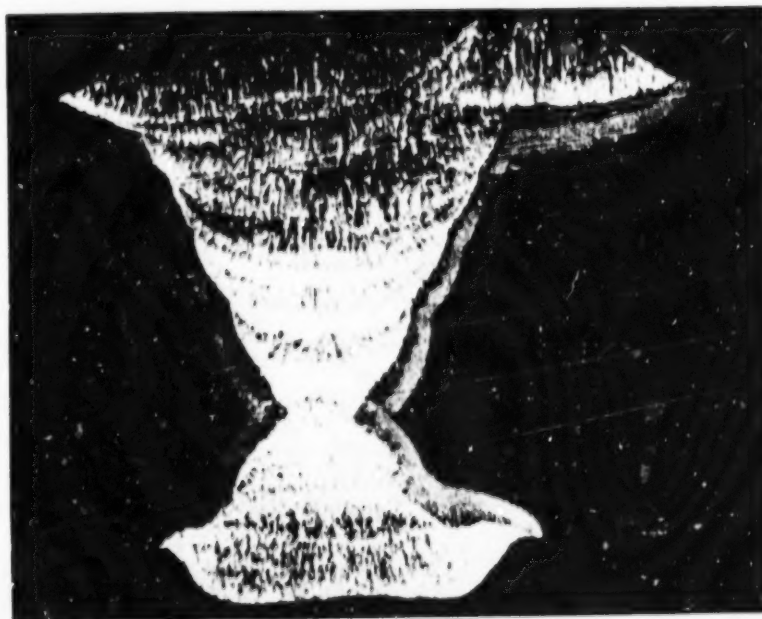
FIGURE 14

Macrosections of Welds Deposited With Alloy Rods IIBON1-1.



a. Direct Current

x2.5



b. Pulsed Current

x2.5

FIGURE 15

Macrosections of Welds Deposited with Kobe DW55L.



a. Direct Current

x2.5

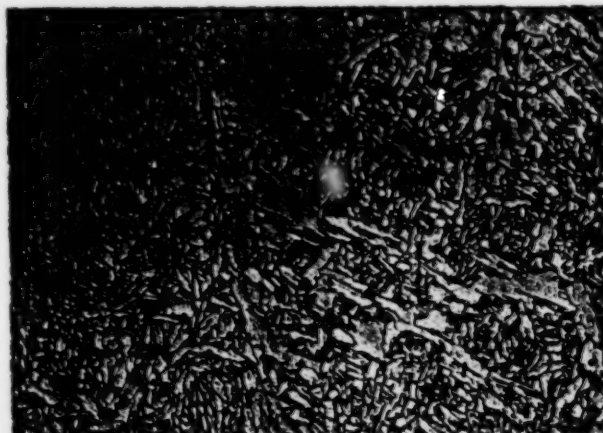


b. Pulsed Current

x2.5

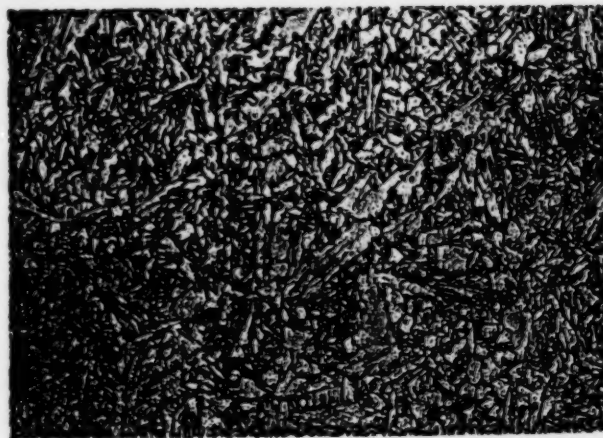
FIGURE 16

Macrosections of Welds Deposited With Oerlikon SF-1.



a. As-Deposited

x500

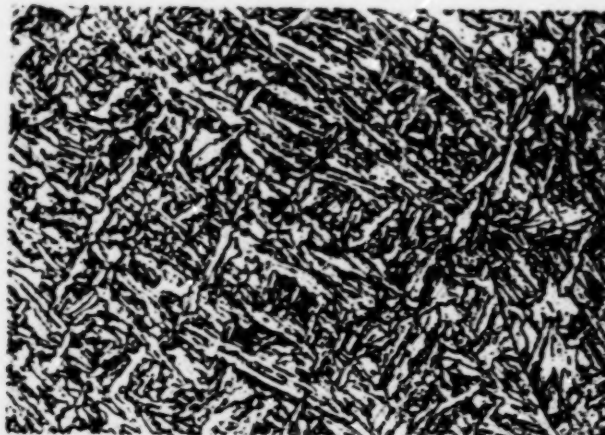


b. Refined

x500

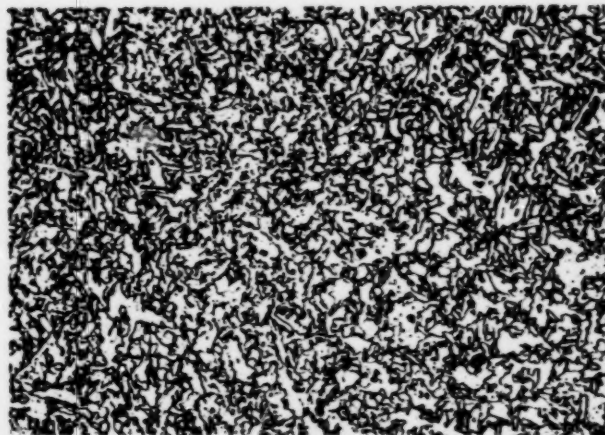
FIGURE 17

Typical Microstructural Features of Welds Deposited
With Alloy Rods I180Ni-1.



a. As-Deposited

x500



b. Refined

x500

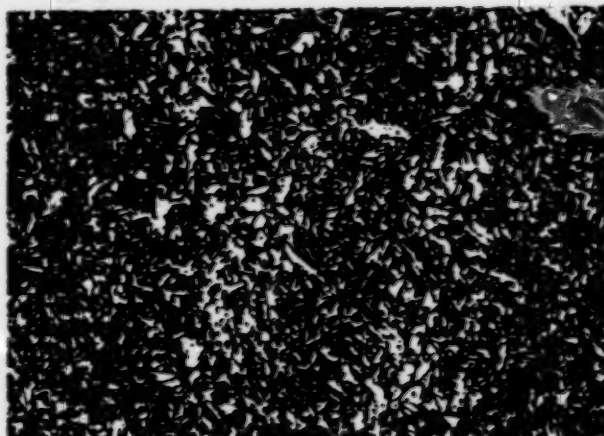
FIGURE 18

Typical Microstructural Features of Welds Deposited With Kobe DW55L.



a. As-Deposited

x500



b. Refined

x500

FIGURE 19

Typical Microstructural Features of Welds Deposited With Oerlikon SF-1.

POOR

QUALITY

ORIGINAL

